Sugar and Ethanol Factory Control

Antonio Carlos Fernandes

The cover image features a photograph by Helder Prado depicting the historical sugar mill Engenho Central. Established in 1881 on the right bank of the Piracicaba River in Brazil it operated until 1971 and now serves as a significant cultural center.

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Antonio Carlos Fernandes

Agronomic Engineer
ESALQ/USP 1972

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Dr. Peter George Wright

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Technical reviewers:

Dr. Peter G. Wright
Danilo Tostes Oliveira

Layout:

Mesly De Nadai Fernandes

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Author

Antonio Carlos Fernandes graduated in agronomic engineering in 1972 (ESALQ USP) and has worked for over fifty years in the sugarcane agroindustry. This includes 27 years at the Copersucar Technology Center, and later as a consultant at sugar and ethanol plants in Brazil and South America. AC Fernandes worked at several companies connected to the sector, primarily at GAtec® as an associate consultant. Author of the Portuguese book "Cálculos na Agroindústria da Cana-de-açúcar" (sold out), which has gone through three editions and had around two thousand copies printed.

Homage

ESALQ
Escola Superior de Agricultura "Luiz de Queiroz" USP University of São Paulo, where the author studied agronomic engineering from 1968 to June 1972 and later Master's in Soils and Plant Nutrition.

COPERSUCAR
Cooperative of sugarcane, sugar, and ethanol producers, where the author worked for 27 years (1972 to 1999) at the Copersucar Technology Center (currently CT Canavieira) in research and development programs.

GAtec® S.A.
Gestão Agroindustrial (*gatec.com.br*), a consulting, training, development, and systems integration company, where the author have been working since 2003 as an associate consultant in the development and configuration of the "Industrial Process Management" system (GAtec® GPI). Visiting several sugar mills in Brazil and abroad to implement this system, he learned about factory control for sugar and ethanol production.

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1 Presentation and basic principles

This publication presents the main descriptions of the technological control of sugar and ethanol production, using the generated data to calculate yields, sugar losses, and factory efficiency. It explains to interested technologists how the calculations of yields and efficiency are conducted in Brazilian mills, where sugarcane is used in the same factory to produce sugar and ethanol simultaneously.

Analytical methodologies are not described with few exceptions, as they can be found in detail in the various existing laboratory manuals. The industrial sugar and ethanol production processes are not described for the same reason. Preference should be given to the ICUMSA (International Commission for Uniform Methods of Sugar Analysis) recommendations in analytical methods.

A major industrial process technological control objective is to determine efficiencies and losses. The results of this control allow the quality monitoring of intermediate and final products (sugar, ethanol, energy, dry yeasts, molasses), making it easier for plant managers and operators to make decisions to maximize company profitability.

Some principles must be followed:

- The simpler the procedures, the more reliable the results will usually be.
- Overcontrol can be as harmful as insufficient control.
- Information is important only when it comes from a reliable source and is usable.

Recommendations were formulated following these principles, including comments and interpretations of the results of technological control of the sugar and ethanol manufacturing process from sugarcane. Almost all Brazilian plants use dedicated software (such

as GAtec-GPI[1]) to control the industrial process, each with its own settings.

- It is recommended to have a manual of standards and procedures to be followed, based on the published laboratory manuals.
- For each stage of the process, there are alternatives for sampling, analysis, and calculations related to the various intermediate materials and products (sugar and ethanol) and for calculations of yields and efficiencies. Each company needs to select the alternative most suitable for them.
- Poor sampling is detrimental to good analytical results while oversampling wastes financial resources and time.
- Increasing the number of decimal places in the calculation does not increase the accuracy or precision of the results. Every method has its inherent precision and accuracy.

[1] *gatec.com.br*

2 Introduction

According to the United Nations Food and Agriculture Organization (FAO, 2020), 92 countries and territories produce sugarcane, and in 56 of them, the total harvested sugarcane exceeded one million tons in 2020[1]. In that year, two-thirds of the total cane was produced in Brazil, India, and China.

Brazil accounts for about 40% (600 million tons) of world sugarcane production ($1.5 * 10^9$ tons), which is processed in 424 sugar and ethanol plants in operation (2022). Brazil is the world's largest sugar producer that uses sugarcane as a raw material for the simultaneous production of sugar and ethanol on a large scale in the same industrial plant and at the same time. This results in some particularities not observed in other countries, especially in controlling and evaluating the industrial process performance. This is essential to optimize yields and efficiencies and thus contribute to the greater economic profitability of the company. A simplified flowchart for sugar and ethanol production in Brazil is shown in **Figure 2.1**.

Important notes on terminology

The following terminology is used to facilitate the calculations presented in this document.

- All **sugar** production was converted to sugar 100% (sucrose) using the polarization of each type of sugar.
- The production of **ethanol**, hydrous or anhydrous, and other derivatives, was converted to ethanol 100% (pure or absolute ethanol) using the alcoholic strength by mass $\%_{m/m}$ and the respective ethanol density (kg/m^3).

[1] https://www.fao.org/faostat/en/#data/QCL

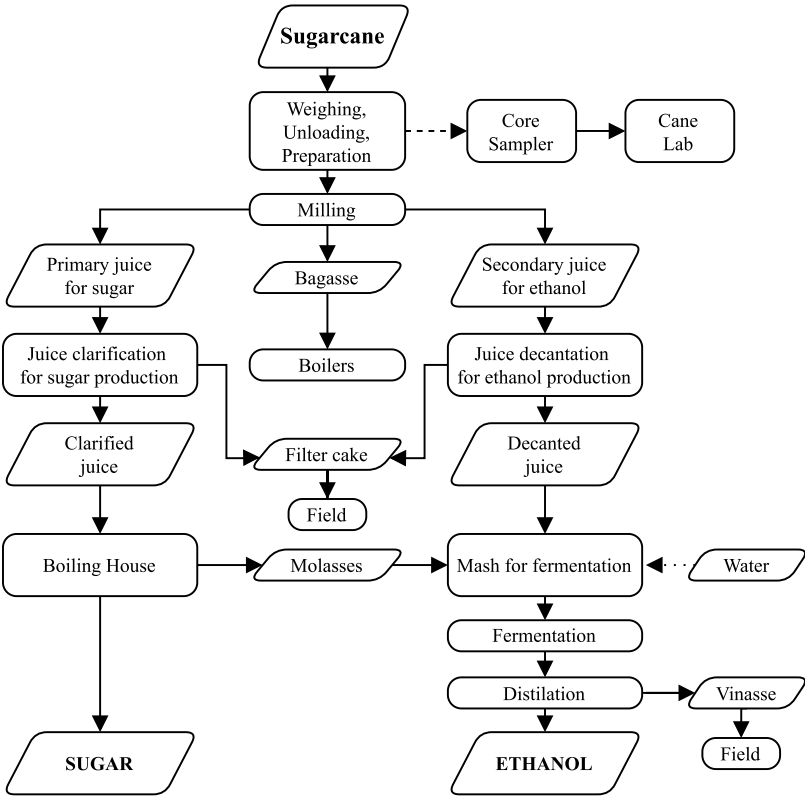

Figure 2.1 – Simplified flowchart of sugar and ethanol production.

- For the presentation of the results, the total "sugar 100%" can be converted back to any type of sugar, and the total "ethanol 100%" can be expressed as hydrous or anhydrous ethanol considering the alcoholic strength and ethanol density.

Therefore, in this publication, the term "**sugar**" means the mass (**kg**) of "**sugar 100%**" or pure sucrose; and "**ethanol**" indicates the volume of 100% ethanol or "absolute ethanol". When not specified, all ethanol volumes are in **liters** at **20 °C**.

When there is the simultaneous production of sugar and ethanol in the same industrial plant, which is common for almost all Brazilian mills, or when B molasses is the final molasses, the control of the industrial process should be conducted in “total reducing sugars” (TRS), as described in this publication.

3 General recommendations for analyses

3.1 Correction of saccharimeter readings

- Lead subacetate (a carcinogenic product) precipitates part of the fructose (levulose, a levorotatory monosaccharide) in the form of "lead levulose", and this increases the reading on the saccharimeter and brings the pol closer to sucrose.
- Dextran, when present in sugarcane juice or sugar solution, has a dextrorotatory effect, which increases the pol reading, the result being called "false pol". Dextran is also partially precipitated by lead subacetate as a laboratory juice clarifier agent.
- Because it is highly polluting and carcinogenic, lead subacetate as a juice clarifier agent was banned in Brazil and several other countries. It has been replaced by other products, such as the "clarifying mixture based on aluminium chloride" and other commercial products, which, however, do not precipitate fructose or dextran, as does lead subacetate.

For the reasons mentioned above, the sugarcane payment system by quality in Brazil (Consecana-SP) establishes a linear regression equation that must be used to convert the saccharimeter reading obtained in the sugarcane juice extracted in the hydraulic press with the utilized clarifying agents to the reading that would have been obtained with lead subacetate.

The equations approved by Consecana-SP are specific for each clarifying agent product and were developed by accredited laboratories, using cane juice extracted in the press in all cases. Therefore these equations should be applied solely and exclusively to the saccharimeter reading data obtained from the cane juice extracted in the hydraulic press.

Applying any Consecana-SP equations to saccharimeter readings obtained with intermediate materials in the process is not recommended. The fructose/sucrose ratio is not the same for all intermediate materials in the industrial process and their saccharimeter results must be interpreted relatively.

3.2 The relationship between pol and sucrose

Traditionally, the sugarcane agroindustry uses two essential measurements: brix (apparent percentage of dry substance determined by spindle or refractometer) and pol (percentage of apparent sucrose determined by saccharimeter). For high-purity materials, such as mature sugarcane juice, it can be assumed that pol can be used as an estimate of sucrose (**Figure 3.1**). However, data obtained for sucrose, glucose, and fructose by high-pressure chromatography (HPLC) or, more recently, by ion chromatography (IC), have shown that there often is a significant difference between pol and sucrose.

In South African mills chromatography has been routinely used since 1985. The "pol cane/ sucrose ratio" between 2001 and 2017 was 0.9929 (source: compiled from "Annual review of the milling season in Southern Africa from 2001 to 2017, SASTA"). For mixed juice, the pol/ sucrose ratio is 0.99 for plants in South Africa and 0.97 for Louisiana, United States (Rein, 2007). This difference may be due to the type of juice clarifier agent used for pol reading in each country.

In the final molasses and low-purity products, the difference between pol and sucrose is more significant, and the lower the purity, the greater the difference. For mixed juice, sucrose is 0.74% higher than pol, in molasses the mean difference is 7.7%

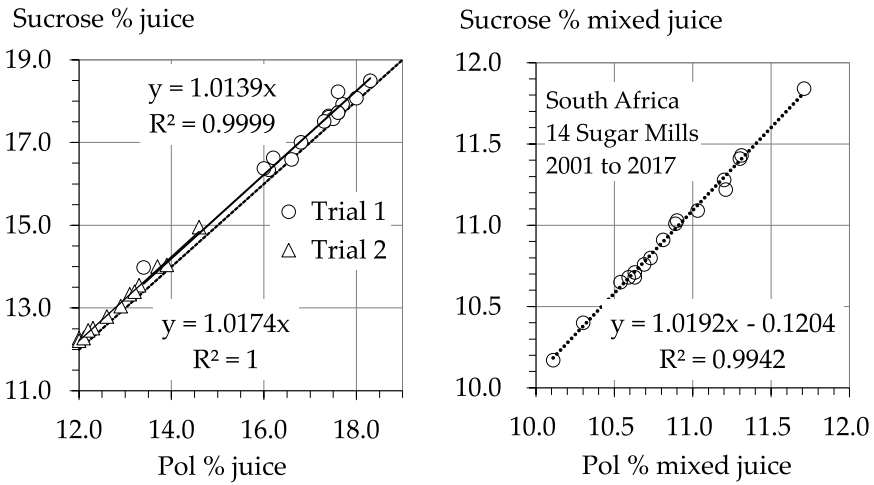

Figure 3.1 – Linear regression between sucrose analyzed by chromatography and pol % cane juice. Left: regression was calculated based on data from Cox & Sahadeo (1992). Right: calculated with the crop means of 14 mills in South Africa (based on data compiled from SASTA, *sasta.co.za*).

3.3 Determined or estimated total reducing sugars?

For Brazilian mills, it is essential to control the process using "total reducing sugars" (TRS), which can be determined by the traditional Lane & Eynon method (1923) or by chromatographic techniques.

However, although these methods are highly precise, they are laborious and time-consuming. Therefore, they are restricted to essential materials, especially for fermentation mash and for final molasses.

For materials with purity > 82%, such as mature cane juice, where pol can be considered the same as sucrose, TRS can be estimated by:

TRS = pol / 0.95 + reducing sugars

The determination of reducing sugars (RS), also by Lane & Eynon, is simpler and faster than the method used for TRS since the latter requires a sucrose inversion step.

Currently, ion chromatography (IC) is used in some Brazilian plants to determine sucrose, glucose, and fructose content. Simple calculations then give a value for reducing sugars (RS) and "total fermentable sugars" (TFS):

$$TFS = sucrose / 0.95 + glucose + fructose$$

TRS includes the "non-fermentable reducing substances", which differentiates it from TFS, formed only by sucrose, glucose, and fructose.

3.4 Juice density as a function of juice Brix

The ICUMSA table of density as a function of the Brix at 20 °C can be divided into sections. Quadratic equations can calculate the density as a function of Brix, specific to the Brix range for each section. The table's determinations would be accurate to about 0.01 kg/m^3.

The equations of Juice density (kg/m^3) versus Brix (%, at 20 °C) can be used in a spreadsheet. The small errors in density prediction do not affect the results of factory control.

Brix from 0% up to 11.5%:

$$\text{Juice density} = 0.014276 * Brix^2 + 3.848694 * Brix + 997.16$$

Brix from 11.6% up to 26%:

$$\text{Juice density} = 0.015726 * Brix^2 + 3.81451 * Brix + 997.36$$

Brix from 70% up to 95%:

$$\text{Juice density} = 0.017458 * Brix^2 + 3.861243 * Brix + 990.60$$

Brix from 91% up to 99%:

$$\text{Juice density} = 0.014712 * Brix^2 + 4.35126 * Brix + 968.77$$

4 Alcoholometry

Alcoholometry is the process of measuring the concentration of ethanol in a mixture of ethanol and water. Technically, ethanol refers to the chemically pure product of the generic formula CH_3CH_2OH or C_2H_6O Absolute alcohol is the product purified and has no trace of water, otherwise, the same as chemically pure ethanol.

Ethanol can be obtained by fermentation of sugary substances (sugarcane juice, molasses), by converting starch (corn and cassava) into fermentable sugars (amylase), or through synthetic processes. In the sugarcane industry, there are names related to ethanol, although the term "ethanol" always refers to a **hydroalcoholic mixture of ethanol with water**.

A distillery can normally produce "hydrous ethanol" and/or "anhydrous ethanol", both for fuel purposes, in addition to "neutral ethanol" or "industrial ethanol", and ethanol with specific quality for exportation. These types of ethanol differ by the **alcoholic strength**, corresponding density, and other physical-chemical characteristics required by the client.

4.1 Alcoholic strength

The alcoholic strength shows the percentage of ethanol in a hydroalcoholic mixture of water and ethanol expressed in two ways:
volume (v/v) or **mass ratio (m/m)**.

The ethanol content found by chromatography in hydrous or anhydrous ethanol may be lower than the value found in digital density meters, since this device includes the determination of other types of alcohol present in the commercial ethanol, such as methanol and higher alcohols.

Alcoholic strength by volume ($\%_{v/v}$)

In a hydroalcoholic mixture, this is measured in a volumetric percentage of ethanol at a given temperature, usually 20 °C (% volume/volume). For example, ethanol with an alcoholic strength by volume of $95\%_{v/v}$ has 95 L of ethanol per 100 L of a solution at 20 °C temperature.

Naturally, because it is a volumetric ratio, the alcoholic strength by volume depends on the temperature and, therefore, this must be specified, and can be scale measured at 15 °C or 20 °C or other, depending on the country.

Alcoholic strength by volume is known historically in Brazil as Gay Lussac degree (°GL). In this publication, the ABNT nomenclature will be used: $\%_{v/v}$. The International Organization of Legal Metrology (OIML, 1973) and the French legislation express the unit of the alcoholic strength by volume as %vol.

Alcoholic strength by mass ($\%_{m/m}$)

It is the mass/mass ratio of the ethanol content in a hydroalcoholic mixture (water and ethanol). The alcoholic strength by mass is a ratio of percentage mass to mass and therefore does not depend on temperature. For example, anhydrous ethanol must be $99.3\%_{m/m}$, i.e., for every 100 kg of the hydroalcoholic mixture there must be 99.3 kg of ethanol, and the difference is formed by water (0.7 kg).

Alcoholic strength by mass or by volume

To produce ethanol, the "alcoholic strength by volume" ($\%_{v/v}$) is used in the fermentation process, since the control is carried out by the volumes of tanks and vats, which allows the "fermentation efficiency" to be obtained.

The alcoholic strength by mass ($\%_{m/m}$) is used to monitor the distillation process and ethanol production, quality, and marketing, carried out by weighing vehicles loaded with ethanol. This data allows the calculation of "distillation efficiency".

The alcoholic strength by mass is not dependent on the ethanol temperature at the time of weighing. Using specific tables, alcoholic mass values are converted to volume and density (kg/m^3) at 20 °C.

Commercial types of ethanol

Currently, the national or international specification for all types of ethanol available on the market depends on each buyer's use directly or for reprocessing. In Brazil, there are four main types of ethanol offered commercially:

Hydrous ethanol: ethanol content between 92.6%$_{m/m}$ to 93.8%$_{m/m}$, i.e., has a mean of 93.2 kg of pure ethanol and 6.8 kg of water per 100.0 kg of hydrous ethanol. It is also called "ethanol" at a gas station or "fuel hydrous ethanol". It can be used as fuel in vehicles with Otto-cycle ethanol-tolerant engines.

Anhydrous ethanol: ethanol with a minimum content of 99.3%$_{m/m}$, i.e., 99.3 kg of pure ethanol and 0.7 kg of water per 100.0 kg of anhydrous ethanol. Also called "anhydrous fuel ethanol" it can be mixed with gasoline and used in vehicles with Otto-cycle petrol engines.

Neutral ethanol: a denomination that encompasses diverse types of ethanol, such as fine ethanol, and extra fine ethanol. Indicates a product with low levels of impurities, used in the beverage, pharmaceutical, and cosmetic industries. Neutral ethanol can be derived from hydrous ethanol or even from anhydrous ethanol.

Industrial ethanol: ethanol produced for generalized industrial purposes, with alcoholic grade and characteristics processed to meet the specifications of the buyer.

4.2 Ethanol volumetric mass density

The ethanol **density** (more precisely, the volumetric mass density; also known as its specific mass) is its mass per unit volume at 20 °C and it is often expressed in SI units as kg/m^3.

"Ethanol density" or "ethanol specific mass" of a given solution can be measured by equipment called density meters or densimeters. These can be glass float types (immersion in liquid) or electronic (digital density meters). For measuring the specific volumetric mass, the most used calibration temperature is 20 °C, and the result can be presented in g/mL, g/cm^3, and kg/m^3 units.

The international standard states that the specific volumetric mass of hydroalcoholic mixtures (density) should be expressed in kg/m^3, at the most usual temperature of 20 °C/4 °C, which relates the specific mass of the solution to 20.0 °C about the specific mass of water at 4.0 °C.

The density or specific mass is directly related to the alcoholic strength. Tables are available for the interconversion of these values.

4.3 Equations for ethanol-specific mass

In 1973, the International Organization of Legal Metrology - OIML[1] presented the document "International Recommendation No. 22 1973", a recognized model for calculating the specific mass of the ethanol hydroalcoholic and water mixture according to the mass ethanol strength at the measurement temperature (t) of the sample.

In 1990, the OIML presented a new fundamental temperature scale, called "International Temperature Scale ITS-90" in place of ITS-68. This incorporated corrections based on the most recent research on standardized fixed temperature points. Following this work or for this reason, Bettin & Spieweck (1990) proposed a new model for

[1] *https://www.oiml.org*

calculating the specific mass of hydroalcoholic mixtures, created from an adaptation of the polynomial presented by the original model of Wagenbreth & Blank (1971), using the same experimental database, duly corrected according to ITS-90.

The Bettin & Spieweck (1990) table

Since 2008, with the adoption of Bettin & Spieweck equation (1990) it is possible to work with temperatures from -20 °C to 40 °C and ethanol strength from zero to 100%$_{m/m}$. This equation will allow the beverage industry, to use the same table as the hydrous and anhydrous ethyl ethanol-producing units.

The equation uses fifty-four coefficients of eight significant digits (**Table 4.1**) to calculate the density "D" (in kg/m^3) of the ethanol and water mixture as a function of the alcoholic strength by mass (ASm) at the sample measurement temperature (t).

Although this is a complex equation, software that performs the calculations of this equation for routine applications was developed by the company GAtec® - Agro-industrial Management[2] in 2008 for ABNT - Brazilian Association of Technical Standards, with support from UNICA - Union of Sugarcane Agroindustry of the State of São Paulo, Brazil[3].

$$\mathrm{D} = A_1 + \sum_{k=2}^{12} A_k * \left(\frac{AS_m}{100} - 0.5\right)^{k-1} + \sum_{k=1}^{6} B_k * (t-20)^k + \\ + \sum_{i=1}^{n} \sum_{k=1}^{mi} C_{i,k} * \left(\frac{AS_m}{100} - 0.5\right) * (t-20)^i$$

[2] *www.gatec.com.br*
[3] *www.unica.com.br*

Table 4.1 – Coefficients of the Bettin & Spieweck equation (1990).

#	Factor	Coefficient	#	Factor	Coefficient
1	A1	913.76673	28	C1.10	-349.32012
2	A2	-221.75948	29	C1.11	1285.9318
3	A3	-59.61786	30	C2.1	$-1.2083196*10^{-4}$
4	A4	146.82019	31	C2.2	$-5.7466248*10^{-3}$
5	A5	-566.5175	32	C2.3	0.12030894
6	A6	621.18006	33	C2.4	-0.23519694
7	A7	3782.4439	34	C2.5	-1.0362738
8	A8	-9745.3133	35	C2.6	2.1804505
9	A9	-9573.4653	36	C2.7	4.2763108
10	10	32677.808	37	C2.8	-6.8624848
11	A11	8763.7383	38	C2.9	-6.9384031
12	A12	-39026.437	39	C2.10	7.4460428
13	B1	-0.7943755	40	C3.1	$-3.8683211*10^{-5}$
14	B2	$-1.2168407*10^{-3}$	41	C3.2	$-2.0911429*10^{-4}$
15	B3	$3.5017833*10^{-6}$	42	C3.3	0.0026713888
16	B4	$1.770944*10^{-7}$	43	C3.4	0.004104205
17	B5	$-3.4138828*10^{-9}$	44	C3.5	-0.049364385
18	B6	$-9.9880242*10^{-11}$	45	C3.6	-0.017952946
19	C1.1	-0.39158709	46	C3.7	0.29012506
20	C1.2	1.1518337	47	C3.8	0.023001712
21	C1.3	-5.0416999	48	C3.9	-0.54150139
22	C1.4	13.381608	49	C4.1	$-5.6024906*10^{-7}$
23	C1.5	-4.5899913	50	C4.2	$-1.2649169*10^{-6}$
24	C1.6	-118.21	51	C4.3	$3.486395*10^{-6}$
25	C1.7	190.5402	52	C4.4	$-1.5168726*10^{-6}$
26	C1.8	339.81954	53	C5.1	$-1.4441741*10^{-8}$
27	C1.9	-900.32344	54	C5.2	$1.3470542*10^{-8}$

The Brazilian Standard ABNT NBR 5992 on "Ethyl ethanol and its mixtures with water - Determination of specific mass and ethanol content - Glass density meter method", including the software developed by GAtec®, can be acquired from ABNT[4]. For the use of digital density meters, the ABNT standard used is ABNT NBR 15639, "Ethanol and its mixture with water – Determination of density and alcoholic strength – Electronic densimetry method".

Simplified equations for alcoholic density

For computer programming or use in spreadsheets, it is easier to use a quadratic regression equation between these parameters, valid only for the following ranges.

a) For **hydrous** alcoholic strength by mass (HASm) in the range between 92.0%$_{m/m}$ to 94.0%$_{m/m}$

$$\text{Hydrous Ethanol Density} = -0.01891510122 * HASm^2 + 0.7544833955 * HASm + 903.175526$$

This equation provides the same results as the Bettin & Spieweck formula (1990), except for differences of -0.01 with hydrous alcoholic strength by mass (HASm) of 93.62%$_{m/m}$, from +0.01 at 92.83%$_{m/m}$ and +0.01 at 92.47%$_{m/m}$. These small differences do not compromise the calculations of the industrial process control.

b) For **anhydrous** alcoholic strength by mass (AASm) in the range between 98.3%$_{m/m}$ to 99.9%$_{m/m}$

$$\text{Anhydrous Ethanol Density} = -0.03678494634 * AASm^2 + 4.212761107 * AASm + 735.808611$$

For the anhydrous alcoholic strength by mass (AASm) ranges, usually checked for anhydrous ethanol (mean specification of 99.3%$_{m/m}$), the

[4] *www.abnt.org.br*

previous equation provides the same density result in kg/m^3 found with the Bettin & Spieweck equation (1990), except for a hundredth difference with a mass grade of 98.6%$_{m/m}$ (793.57 kg/m^3 for the simplified equation versus 793.56 kg/m^3 for Bettin & Spieweck, 1990).

Important: These two simplified equations should not be applied outside the mentioned ranges of mass alcoholic strength.

4.4 Mass and volumetric alcoholic strength

Knowing the alcoholic strength by mass (%m/m) and obtaining the density (kg/m^3 at 20 °C) of the hydroalcoholic mixture at 20 °C in reference tables, it is possible to calculate the corresponding alcoholic strength by volume (%$_{v/v}$):

Alcoholic strength by volume = Alcoholic strength by mass * Ethanol density / **789.23**

Conversely, knowing %$_{v/v}$ it is possible to get %$_{m/m}$ by:

Alcoholic strength by mass = Alcoholic strength by volume * **789.23** / Ethanol density

789.23 = density of ethanol 100% at 20 °C (kg/m^3)

Note: The density can be obtained by the ABNT software mentioned above or by the quadratic equation presented in the earlier item for the ranges of hydrous ethanol or anhydrous ethanol.

Example

Ethanol with an alcoholic strength by mass of 93.5%$_{m/m}$ means that in 100 kg of the hydrous mixture, there is 93.5 kg of ethanol.

Hydrous Ethanol Density = -0.01891510122 * 93.5^2 + 0.7544833955 * 93.5 + 903.175526 = 808.36 kg/m^3

Correspondent hydrous alcoholic strength by volume:

$$95.77\%_{v/v} = 93.5\%_{m/m} * 808.36\ kg/m^3\ /\ 789.23\ kg/m^3$$

Conclusion: alcoholic strength by mass of $93.5\%_{m/m}$ corresponds to alcoholic strength by volume of $95.77\%_{v/v}$.

4.5 Volume correction coefficient (VCC)

Although the Brazilian standard specifies the measurement of an alcoholic strength by mass ($\%_{m/m}$) and the ethanol density (kg/m^3) at a temperature of 20.0 °C, all production and stock measurements are volumetric and performed at room temperature. Thus, it is necessary to correct the volume measured at different temperatures to the standard temperature of 20.0 °C through the "volume correction coefficient" (VCC), before applying the results of the analytical determinations.

The VCC according OIML (1973)

For International Organization of Legal Metrology OIML (1973) the VCF at 20.0 °C must be calculated by the equation:

$$VCC_{20°C} = \frac{ED(AS;t)}{ED(AS;20C)} * (1 + 36.10^{-6} * (t - 20))$$

Where:

ED(AS;t) = ethanol density (kg/m^3) at measuring temperature "t" (°C) for alcoholic strength by mass (AS) ($\%_{m/m}$).

ED(AS;20 °C) = ethanol density corrected to 20.0 °C (kg/m^3) t = temperature observed during ethanol volume measurement (°C)

Coefficient **36.10^{-6}** represents the cubic coefficient of steel expansion. In 2016 a new version of norm ABNT NBR 5992 eliminated this storage device correction. The software developed by GAtec for the Brazilian Standard ABNT NBR 5992 mentioned before provides the VCC value together with the alcoholic strength by mass $\%_{m/m}$ and alcoholic strength by volume $\%_{v/v}$.

Example A (using a digital density meter)

The volume of ethanol was obtained at a temperature of 27.5 °C and the alcoholic strength by mass was measured in a digital density meter at 20.0 °C. This is the most common situation in Brazilian distilleries.

Analytical data:

Temperature during volume measurement	27.5 °C
Alcoholic strength by mass	99.50%$_{m/m}$

Results:

Alcoholic strength by volume at 20.0 °C	99.70%$_{v/v}$
Ethanol density at 20.0 °C	790.80 kg/m^3
Ethanol density at 27.5 °C	782.31 kg/m^3

$$VCC_{20°C} = (782.31 / 790.80) * (1 + 0.000036 * (27.5 - 20)) = 0.9895$$

In this example, the observed volume of ethanol at 27.5 °C must be multiplied by 0.9895 to correct for the standard temperature of 20.0 °C.

Example B (using a glass density meter)

The volume of ethanol was obtained at a temperature of 25.0 °C and the ethanol density was measured in a glass density meter (glass float gauge hydrometer) at 21.5 °C.

Analytical data:

Temperature during volume measurement	25.0 °C
Temperature during analytical readings	21.5 °C

Results:

Alcoholic strength by mass	93.45%$_{m/m}$
Alcoholic strength by volume at 21.5 °C	95.55%$_{v/v}$
Alcoholic strength by volume at 20.0 °C	95.73%$_{v/v}$

Ethanol density at 20.0 °C	808.50 kg/m^3
Ethanol density at 21.5 °C	807.00 kg/m^3
Ethanol density at 25.0 °C	803.45 kg/m^3

$$VCC_{20°C} = (803.45 / 808.50 * (1 + 0.000036 * (25.0 - 20)) = 0.9939$$

Example C (using a glass density meter)

In this example, the volume of ethanol (m^3) was measured at a temperature of 18.5 °C, and the alcoholic strength by volume using a glass float gauge hydrometer at a temperature of 21.2 °C.

Analytical data:

Temperature during volume measurement	18.5 °C
Temperature during analytical readings	21.2 °C
Alcoholic strength by volume at 21.2 °C	95.50%$_{v/v}$

Results:

Alcoholic strength by mass	92.87%$_{m/m}$
Alcoholic strength by volume at 20.0 °C	95.33%$_{v/v}$
Ethanol density at 20.0 °C	810.10 kg/m^3
Ethanol density at 18.5 °C	811.60 kg/m^3

$$VCC_{20°C} = (816.60 / 810.10) * (1 + 0.000036 * (18.5 - 20)) = 1.0018$$

4.6 Equivalent volume of absolute ethanol

Brazilian distilleries produce more than one type of ethanol (anhydrous, hydrated, second, or industrial), or the same type of ethanol with different alcoholic strengths during the milling period. To sum the volumes of different types of ethanol, it is necessary to obtain the corresponding volumes as "absolute ethanol" or ethanol 100%.

When multiplying a certain volume in cubic meters (m^3) of ethanol at 20.0 °C by its density (kg/m^3) the corresponding mass of ethanol is obtained in kilogram, which must be multiplied by the alcoholic strength

by mass ($\%_{m/m}$) to result in the volume of ethanol contained in the known volume of ethanol. Generically, a given volume of ethanol (m^3) can be theoretically transformed into another volume of ethanol with a different alcoholic strength by mass ($\%_{m/m}$) using the formula:

$$\text{Expected ethanol volume} = \frac{\text{Known volume of ethanol at 20.0 °C} * \text{Known alcoholic strength by mass} * \text{Known density at 20.0 °C}}{\text{Expected alcoholic strength by mass} * \text{Expected density at 20.0 °C}}$$

Where volume is in cubic meters (m^3) at 20.0 °C; alcoholic strength by mass ($\%_{m/m}$) and density in kg/m^3.

Examples of the volume conversion of cases are shown in **Table 4.2**. The ethanol density (kg/m^3) was obtained by the Bettin & Spieweck (1990) equation (OIML).

Table 4.2 – Example of conversion of one type of ethanol to another one (all temperatures at 20.0 °C).

Description	Unit	Case A	Case B
Ethanol to be converted	L	1000	1000
Known alcoholic strength	$\%_{m/m}$	99.45	93.50
Known alcoholic strength	kg/m^3	790.95	808.12
Alc. strength to be obtained	$\%_{m/m}$	93.50	99.45
Ethanol density	kg/m^3	808.36	791.13
Obtained ethanol	m^3	1040.728	960.362
Water to be added or evaporated	L	40.728	-39.638

4.7 Fixed ethanol conversion factors

The "ethanol conversion factor" allows several types of ethanol (hydrous, anhydrous, industrial ethanol) to be converted into an-

other type using the standards specification for these products (**Table 4.3**).

Table 4.3 – Transformation factors of known volumes of ethanol (all temperatures at 20.0 °C), anhydrous and hydrous with the mean alcoholic strength by mass and density calculated by the Bettin & Spieweck equation (1990)..

Results	**Ethanol**	**Hydrous**	**Anhydrous**
Alc. strength $\%_{m/m}$	100	93.2	99.5
Density (kg/m_3)	789.23	809.19	790.80
Alc. strength $\%_{v/v}$	100.0	95.56	99.70
	Multiply by the factors below to get:		
Known volume↓	**Ethanol**	**Hydrous**	**Anhydrous**
Ethanol	1.00000	1.04650	1.00303
Hydrous	0.95557	1.00000	0.95847
Anhydrous	0.99698	1.04333	1.00000

For example, to convert a known volume of anhydrous ethanol into hydrous ethanol (both at 20.0 °C), multiply by 1.0433.

Important: For different alcoholic strengths by mass, the ethanol density at 20 °C (kg/m^3) must be calculated by the Bettin & Spieweck equation (1990).

5 Stoichiometry

Stoichiometry is the branch of chemistry concerned with the proportions in which elements are combined in compounds and the quantitative relationships between reactants and products in chemical reactions.

This chapter deals with the concepts that are applied to the rules for stoichiometric conversion of sugars into ethanol and vice versa.

5.1 Commercial sugar conversion into sucrose

For the conversion of the distinct types of sugar produced from sugarcane into sucrose, also called "sugar", the sugar mass must be multiplied by the corresponding pol % sugar. In this way, it will be possible to sum up all types of sugar produced.

Total sucrose production (kg) = Total commercial sugar (kg) * Pol % sugar / 100

5.2 Commercial sugar purity, "True" and "Apparent"

Actual, or "True" sugar purity is the percentage of sucrose in the dry matter or dissolved solids content (DS). DS is made up of sucrose plus non-sucrose components such as inverted sugars, ash, colorants, and other minor components. An approximation to True Purity is "Apparent purity" which is expressed as pol divided by refractometer Brix, multiplied by 100.

The apparent purity of sugar (percentage of pol contained in sugar brix) can be calculated by assuming that one hundred minus sugar's moisture equals the brix of sugar.

Sugar purity = 100 * Pol % sugar / (100 - Moisture % sugar)

Naturally, this result does not represent the percentage of soluble solids in sugar (brix). Still, in high-polarization sugar, the presence of non-sucrose components is negligible for factory process control.

For example, for sugar with pol of 99.72 °Z and moisture of 0.04%, the purity will be 99.76%. For high-polarization white sugars, for practical purposes, purity can be considered equal to 100%.

5.3 Sucrose conversion into inverted sugar

In the presence of certain enzymes or under acid reaction and adequate temperature, sucrose absorbs a molecule of water and is divided into an equimolecular mixture formed by one molecule of glucose and one of fructose (inverted sugar).

$$\underset{\substack{342.2992\ g\\ \text{sugar}}}{C_{12}H_{22}O_{11}} + \underset{\substack{18.0152\ g\\ \text{water}}}{H_2O} \rightarrow \underset{\substack{180.1572\ g\\ \text{glucose}}}{C_6H_{12}O_6} + \underset{\substack{180.1572\ g\\ \text{fructose}}}{C_6H_{12}O_6}$$

Considering the exact atomic mass values of carbon (C) equal to 12.011, hydrogen (H) equal to 1.0079, and oxygen (O) equal to 15.9994, the molecular mass of water is equal to 18.0152, that of glucose, or fructose ($C_6H_{12}O_6$) is 180.1572 and that of sucrose ($C_{12}H_{22}O_{11}$) is equal to 342.2992.

Thus, 342.2992 g of sucrose absorbs 18.0152 g of water to produce 360.3144 g of "inverted sugar" (equimolecular mixture of glucose and fructose from sucrose inversion). Proportionally, 100 g of sucrose will produce 105.263 g of inverted sugar, or 95 g of sucrose is required to produce 100 g of inverted sugar.

Dividing the known sucrose mass (sugar) by 0.95, correspondent inverted sugar is obtained. Conversely, the sucrose mass can be multiplied by 1.05263 for the same result.

Inverted sugar = Sucrose $*$ 2 $*$ 180.1572 / 342.2992

Sucrose (pol) to inverted sugar	→	Divide by 0.95
Reducing sugars to sucrose	→	Multiply by 0.95

That is, the same factor is used for both directions, which avoids rounding errors and factor confusion.

For example, the production of 305,480 kg of sucrose corresponds to: 305,480 kg / 0.95 = 321,558 kg of inverted sugar

5.4 Total reducing sugars (TRS)

Total reducing sugars (TRS) represent all sugars in sugarcane (sucrose, glucose, and fructose, mainly) in the form of reducing sugars or inverted sugar.

TRS can be determined directly in several materials with sugars, such as sugarcane juice, mash or wort, syrup, and molasses, by various techniques, such as oxidoreductimetry (the traditional method of Lane & Eynon, 1922), colorimetry, and chromatography.

When the components of the reducing sugar content are determined, total fermentable sugars (TFS), basically the same as TRS, can be calculated by the equation:

TFS = Sucrose / 0.95 + Glucose + Fructose

Alternatively, for high-purity materials, such as mature sugarcane juice, considering that the sucrose content does not differ significantly from pol, it can be approximated that:

TRS = Pol / 0.95 + Reducing sugars

This equation is acceptable for levels lower than 1.5% of reducing sugars % juice, i.e., it cannot be applied in syrup, final molasses, and mash with a mixture of juice and molasses. For these materials, the direct determination of TRS is mandatory for the correct control of the sugar

and ethanol manufacturing process. For example, the pol % juice is equal to 17.17% and reducing sugars % juice equal to 0.46%, then:

Total reducing sugars = 17.17 / 0.95 + 0.46 = 18.53

This procedure simplifies and reduces the costs of factory control for several materials of high purity or lower levels of reducing sugars.

For lower-purity syrups and molasses, it is necessary to use analytical procedures, such as chromatographic methods, to determine the values of sucrose, glucose, fructose, and other components of reducing sugars, including some "non-fermentable reducing substances".

5.5 Stoichiometric yield of yeast fermentation

The stoichiometric yield of fermentation is the chemical conversion of all sugars present in the mash into ethanol, with no sugar losses.

Monosaccharides (reducing sugars or inverted sugar) are directly fermented for ethanol production through alcoholic fermentation. The sucrose molecule is broken by yeast enzymes into two inverted sugar molecules, before being transformed into ethanol.

Sucrose equivalence as ethanol

Alcoholic fermentation is a complex biochemical process involving multiple stages of sugar transformation by yeast. After the inversion of sucrose in glucose and fructose, these molecules can be directly fermented for conversion into four ethanol molecules and four carbon dioxide molecules.

$$\underset{\substack{342.2992\ g\\ \text{sucrose}}}{C_{12}H_{22}O_{11}} + \underset{\substack{18.0152\ g\\ \text{water}}}{H_2O} \rightarrow \underset{\substack{2*180.1572\ g\\ \text{inverted sugars}}}{2*C_6H_{12}O_6} \rightarrow \underset{\substack{4*46.0688\ g\\ \text{ethanol}}}{4*CH_3CH_2OH} + \underset{\substack{4*44.0098\ g\\ \text{carbon dioxide}}}{4*CO_2}$$

Stoichiometrically, 342.2992 g of sucrose produces 360.3144 g (2∗180.1572) of total reducing sugars, which in turn produce 184.2572 g (4∗46.0688) of ethanol, i.e., each kilogram of sucrose corresponds to 4∗46.0688 / 342.2992 = 0.538345 kg of ethanol (ethanol). This ethanol mass can be transformed into a volume of ethanol using the density of ethanol at 20.0 °C of 789.23 kg/m^3.

$$\underset{\text{sucrose}}{342.2992\text{ kg}} \rightarrow \underset{\text{ethanol}}{4*46.0688\text{ kg}} \rightarrow \frac{1000*4*46.0688\text{ kg}}{789.23\text{ kg/L}} \rightarrow \underset{\text{ethanol}}{0.682115\text{ L}}$$

A certain amount of sucrose (kg) can be converted stoichiometrically into ethanol (L) by multiplying by the coefficient 0.682115, and vice-versa. This volume of ethanol in turn can be converted into hydrous or anhydrous ethanol as demonstrated in the previous item.

Sucrose to ethanol	→	Multiply by 0.6821
Ethanol to sucrose	→	Divide by 0.6821

Total reducing sugars (TRS) equivalence as ethanol and vice versa

The exact atomic mass values of carbon (C) are equal to 12.011, hydrogen (H) equal to 1.0079, and oxygen (O) equal to 15.9994. With these values, the molecular mass of inverted sugar or glucose or fructose ($C_6H_{12}O_6$) is equal to 180.1572, ethanol (CH_3CH_2OH) is 46.0688 and carbon dioxide (CO_2) is 44.0098.

Each molecule of total inverted sugar (or total reducing sugars) is fermented for conversion into two ethanol molecules and two carbon dioxide molecules.

$$\underset{\substack{342.2992\text{ g}\\ \text{total reducing sugars}}}{C_6H_{12}O_6} \rightarrow \underset{\substack{2*46.0688\text{ g}\\ \text{ethanol}}}{2*CH_3CH_2OH} + \underset{\substack{2*44.0098\text{ g}\\ \text{carbon dioxide}}}{2*CO_2}$$

This chemical equation shows that 180.1572 g of total reducing sugars (TRS) produce 92.1376 g (2*46.0688) of ethanol, that is, each kilogram

of TRS corresponds to 0.511429 (100 * 2 * 46.0688 / 180.1572). The ethanol mass divided by the ethanol (100 $\%_{m/m}$) density at 20.0 °C (789.23 kg/m^3) results in 0.648010 L of ethanol per kg of TRS. This result is called "stoichiometric yield of fermentation", that is, the volume in liters of ethanol that can be produced per kilogram of TRS with a fermentation efficiency of 100%. This is the correct value to be used in stoichiometric calculations.

TRS in ethanol → Multiply by 0.6480
Ethanol in TRS → Divide by 0.6480

That is, only one factor for both directions, which avoids rounding errors and coefficient con-fusion.

When the approximate values (integers, without decimals) of atomic mass for carbon (C), hydrogen (H), and oxygen (O) are used, the factor 0.6475 L of ethanol per kg of TRS is obtained. With the correct atomic mass values, the factor obtained is 0.6480, as demonstrated before. This change was suggested in 2005 by Dr. Peter G. Wright, PGW ProSuTech, Australia.

Anhydrous or hydrous ethanol equivalence as TRS

Considering the produced ethanol volume (m^3 at 20.0 °C), alcoholic strength by mass ($\%_{m/m}$), and ethanol density (kg/m^3; at 20.0 °C) each type of ethanol (hydrous, anhydrous, etc.) should be converted into ethanol type (m^3 at 20.0 °C) using the following formula.

Corresponding ethanol volume = Known volume of ethanol ∗ Known alcoholic strength by mass ∗ Known density / 789.23

In this way, the volumes of the distinct types of ethanol can be summed up to obtain the total ethanol produced and this result is divided by 0.6480 to obtain the corresponding stoichiometric mass of total reduction sugars (TRS).

6 Cane sampling and preparation for analysis

Sugarcane is the most variable material in a sugar-ethanol plant, especially in the initial and final months of the harvest season. The cane feedstock requires special attention to cane sampling and analysis for industrial processing.

Botanically, sugarcane can be defined as a plant formed by a stool containing several stalks, with the primary stalk formed from the same bud.

For industrialization, the term "cane" (raw material or gross cane) generally refers to sugarcane stalks cut close to the ground, containing a certain quantity of "impurities" or "trash", "tops" and "soil". These impurities could be better called "non-stalk".

In manual harvesting, the stalks are hand cut after the sugarcane field has been burned ("burned cane"), topped in the last mature node ("breaking point"), and placed on the ground for mechanized loading ("grab loaders"). The mechanized loading results in the addition of "impurities", mainly clay soil ("dirt") adhering to the stalks.

When mechanically harvested unburnt cane ("green cane") using chopper harvesters, the chopped stalks are partially cleaned by blown air and loaded directly onto transport or transshipment vehicles. In this system, almost all the "non-stalks" are formed by green leaves, partially dry or dry leaves, sheaths, tops, and, rarely, weeds. Some soil is also included. Clay soil may adhere to the chopped cane in excessive amounts during wet weather conditions. Mechanically harvested burnt cane has lower quantities of leafy matter than unburnt cane.

Cane sampling techniques

For the factory performance results to be accepted, as well as the mass balance of sugars (pol, sucrose, or TRS) and the "undetermined

losses", it is essential that the procedures for sampling cane, the preparation of the sample, the technological analysis and the calculations are rigorously correct and validated. This will prevent the factory control from showing grossly unreal undetermined sugar losses.

All models of industrial efficiency calculations are based on the results of cane quantity and measurements. The sugarcane payment system uses these same results, and they are also used to evaluate the field performance.

Methods that can be used for cane sampling at the factory vary. Some of these are:

1. Sampling directly on transport vehicles.
    - Horizontal core sampler (on rails or tractor).
    - Oblique core sampler (the recommended technology for Brazilian sugar mills).
2. Sampling after preparation of the raw material with knives and hammers before extraction of the juice by the mill or diffuser, as usual in South African sugar mills.
3. By sampling the first expressed juice, with associated cane fiber determination of the relevant variety. This has been the traditional system for Australian sugar mills.

6.1 Sampling prepared cane for milling

Prepared cane samples (shredded cane) can be used to obtain technologically-quality data on the cane. This method is only suggested in Brazilian sugar mills when the core sampler and press methods are not available for more than one or two days.

Shredded cane sampling

The manual grab sampling of the prepared cane on the "fast belt" is laborious and may be not accurately representative of the raw material processed. This can compromise the quality of the results of industrial efficiency and the mass balance of sugars. This inaccuracy is because, as Hugot (1974) has shown, the prepared cane collected in the "fast belt", after the knives, hammers, and shredders and before the first mill, is deposited in layers, in the upper part of the cane mattress is the largest portion of the sugarcane fiber and in the lower layer the inner part of the cane, which has a higher density.

When there is cane washing, sugar losses occur, especially those exuded and adhered to the rind due to the field burning before harvest, and there is also the dilution effect because the stalks absorb water. Thus, the shredded cane presents different weights and compositions from the raw material (stalks or chopped cane, trash, soil) that passed through the scale.

During cane preparation by knives, hammers, and shredders there are physical losses of cane pieces that will not be included in the sample of prepared cane.

With the sampling of shredded cane for milling there is the extra work of identifying the origin of the raw material for payment purposes to the grower, which is not always possible in a routine process.

In South African mills, the batch collection of shredded cane is executed automatically. A hatch located on the mat opens for a few seconds and a large amount comprising the full depth of cane is separated for analysis. The action is timed to correspond with the passage of cane related to a targeted supplier. The material is subsampled and the subsample is then analyzed by the wet disintegrator method using high-speed disintegrator equipment with dimensions larger than the Brazilian version of the disintegrator.

Analysis of the prepared cane analysis

The sample of "shredded cane" is analyzed by the wet disintegrator method or the press method.

In the press method the linear regression equation for the estimation of the fiber % cane as a function of the mass of wet bagasse remaining after the press and also the equation of the coefficient "c" were developed with samples of finely shredded cane. This is not the case for samples of shredded cane for milling. For this reason, the cane samples should be first prepared in a dry disintegrator. This entails more work and may cause changes in the results due to the loss of moisture from the sample, some consumption of sugars by bacteria, and some enzymatic inversion of sucrose.

6.2 Cane analysis by the core sampler and press method

The core-press method has been used in Brazil since 1972 when Copersucar (a non-governmental cooperative of sugarcane, sugar, and ethanol producers) imported from France two horizontal core samplers (Fapmo; **Figure 6.1**) and two hydraulic presses (Pinette-Emidecau).

Figure 6.1 – First FAPMO horizontal core sampler operating in 1972 at Copersucar Sugarcane Laboratory installed at Usina Da Barra, Barra Bonita SP Brazil.

At some Brazilian sugar/ethanol mills it was found that the core method has greater ease of sampling than does shredded cane. An oblique or horizontal core sampler leads to more representative results since with the core corer/press system, hundreds of samples identifiable per truckload can be sampled and evaluated daily (**Figure 6.2**; **Figure 6.3**)

The main advantage of sampling with a probe directly on the transport vehicles is the better identification of the sample, making it possible to control the delivery of cane by the independent producer or by place of origin (farm, plot, variety). It also allows controlling the soil level in the cane and the origin of impurities in the field by location, by machine (loader, harvester), and by operator. The major disadvantage is the high initial cost of the system, with substantial implementation, operation, and maintenance expenses. However, the results can be highly rewarding.

Figure 6.2 – Two oblique core samplers operating side by side in 2008 at Usina Da Barra, Barra Bonita/SP Brazil (author's photo).

Figure 6.3 – Horizontal (old model) and oblique core sampler operating in 2008 at Usina Iracema, Iracemápolis/SP Brazil (author's photo)

6.3 Population and sampling

In statistics, it is important to define the population to be sampled and with what degree of precision the results must be obtained, that is, what error is acceptable. This precision depends on the parties interested in the results: whether they be field or cane owners, factory management, or independent cane producers.

Due to the different criteria for weighting the means of the analytical results, the final values presented to each interested party may contain some small differences.

Sampling for field purposes

For the cane produced by the mill (own plantations), the ideal is to establish the sampling of cane by "sector" or "block of plots", which must be delimited as an area formed by a set of homogeneous sugarcane plots, with the same variety, planted and harvested within a maximum period of 15 days, with the same type of soil and/or "production

environment", without "signals" of aerial or underground pests, diseases, or weed infestation.

With all these restrictions it can be, in some situations, difficult to group plots into blocks, but this procedure facilitates the authorization for harvesting when the quality of the cane is approved, speeds up agricultural operations, and improves the identification of sugarcane samples.

Sampling for cane grower's information

The cane suppliers are the third party interested in monitoring the cane quality results. In São Paulo, Brazil, growers are remunerated based on the fortnightly mean of cane payment quality system of Consecana-SP. In Brazil, the recommendation is for sampling per block of plots delivered in the fortnight, controlled by the "authorization code" for harvest.

If more than one block is harvested in a fortnight, they must be treated separately, in the same way when a block is harvested in two consecutive fortnights. To meet the block concept, the harvest period for each block cannot be longer than 15 days.

Sampling for factory control purposes

From the factory aspect, the population represents all the loads of cane delivered on the day, and the most important technological component is the "total reducing sugars" (TRS) which can include fiber % cane, pol % cane, and estimations of trash and soil inherent in the cane.

6.4 Core sampling of cane in truckloads

The "Manual Consecana-SP" (rules of sugarcane payment system in Brazil) outlines the minimum number of samples to be collected by horizontal sampling probe (core sampler) with three holes in the load per sample; or by oblique core sampler with one hole per

sample, mandatorily with double entry at the same sampling point (**Table 6.1**).

Table 6.1 – Sugarcane sampling recommended by "Consecana-SP Manual" 6th edition, valid since 2014, by field block of plots (grower or sugar mill own cane). The % sampled in the third column is considering the upper limit of the delivery range per day.

Deliveries/day	Samples/day	% sampled
1 to 5	All	100
6 to 7	5	71
8 to 10	8	80
11 to 15	10	67
16 to 25	12	48
26 to 35	13	37
36 to 45	15	33
46 to 55	16	29
56 to 70	17	24
71 to 85	19	22
86 to 100	20	20
>100	>23	25%

General recommendations for sugarcane sampling

A sugarcane analysis laboratory having one oblique core sampler, two disintegrators (one reserve), one hydraulic press, and working with three analysts per shift of eight hours each (four analysts in the daytime) should be able to perform analysis of 200 samples/24 working hours.

The sugarcane laboratory (cane lab) should always work at its maximum capacity, setting a minimum objective of sampling around 33% of the total cane loads delivered per day. On days or periods with a low amount of cane delivered to the mill, all loaded trucks must be

sampled and analyzed, taking into account the maximum capacity of the cane lab.

To validate the cane sampling system, a linear regression between the daily means of the measurements of brix % juice from the press and the brix % first expressed juice, the juice extracted in the first two grinding rolls of the milling tandem, can be checked. When it is not possible to sample the first expressed juice, primary juice (first milling set of the tandem) can be used.

For a period longer than one month, there must be a significant linear regression between these variables. Considering the total harvest period, the coefficient of determination (R^2) must be above 0.85. A correlation lower than 0.85 indicates poor sampling either of the primary juice or of the cane. Most likely it will be a poor sampling of the cane.

6.5 Cane sample preparation for analysis

In 1972 two Jeffco[1] cane disintegrators were imported by Copersucar from Australia to be used with the horizontal sampler (Fapmo) and hydraulic press (Pinette-Emidecau) imported from France. These equipment were installed at Usina da Barra to study a cane quality payment system.

The Copersucar team did not approve the Jeffco disintegrator (1972 old model) (there was no Consecana at that time) for the sample preparation used with the core/press system. This was due to some juice extraction and cane heating during the sample preparation. For this reason, a disintegrator produced by Penha[2] and used to prepare sugarcane and other plants for animal feed was modified and adopted by the Copersucar team to prepare the cane sample. At first, the cane prepared by the modified disintegrator was manually homogenized.

[1] *jeffress.com.au*
[2] *www.penha.ind.br*

Later on, to facilitate and speed up this work, a modified concrete mixer was adapted to mix the output of the disintegrator.

The fine state of the cane after disintegration, which operated without extracting any juice and more quickly than the Jeffco disintegrator, facilitates the homogenization and subsampling of the cane for analysis. Therefore, several companies in Brazil have produced similar equipment and models. This system is still operated today in more than 400 sugar mills in Brazil during the last 50 years.

The samples for analysis are efficiently prepared in less than three minutes in the Brazilian type disintegrator.

Equipment for cane sample preparation

The cane samples from the core sampler, with a minimum mass of 10 kg, are prepared in the disintegrator and mechanically homogenized with an adapted concrete mixer called a "homogenizer set" (**Figure 6.4**).

Figure 6.4 – Adapted disintegrator and concrete mixer used for cane preparation for analysis.

In many Brazilian mills, the cane sample collected with the core sampler is sent through a tube to the disintegrator's reception box, where it

is inspected to prevent the ingress of stones and metal, and then moved into the disintegrator.

The cane sample preparation for analysis in the cold extractor, as well as for the press method, should result in fine particles without any juice extraction loss. This fine preparation facilitates the sample homogenization and the collection of a representative subsample, with high sugar extraction by the equipment (extractor or press).

For the cane analysis method evaluation, it is important to consider the work of the harvesters and the core sampler under poor harvesting conditions (**Figure 6.5**). Of course, extreme situations like these are rare and do not unduly influence the results of the crop season.

Figure 6.5 – Sugarcane sample with excess soil (left, infrequent situation) and sample from the core-sampler with the cutting tube crown shredding the cane (right). Bellow, a sample of the resulting disintegrated cane for the press.

Usually, sampling sugarcane with an oblique probe and preparing it for analysis in an adapted forage-type disintegrator is highly efficient and very fast, even when performed on unburned cane harvested by

chopper harvesters, as long as the equipment is well maintained and sharpened (**Figure 6.6**).

Figure 6.6 – Good cane sample preparation (left) and by disintegrator with bad maintenance (right).

The estimation of "non-stalk" (trash, impurities) can be done directly by hand cleaning the sample from the core sampler (**Figure 6.7**). A small part of the same sample, after disintegration, can be incinerated to estimate the amount of soil (mineral trash) carried with the cane.

Figure 6.7 – Cane from core sampler being hand cleaned for estimation of non-stalk fractions.

These facilities of trash measurement are not possible when using the factory shredded cane for milling, as adopted by South African mills, or when sampling the first expressed juice, as is the Australian method.

The chopped samples from the core sampler must be analyzed immediately to minimize losses of moisture and deterioration. After the disintegration of these samples, the extraction of the juice with the press must be carried out with minimum delay for the same reason.

7 Cane quality evaluation

The pol % cane and the juice purity are the main indicators of the cane quality for industrialization, as they show the amount of sugar (pol) available to produce sugar and/or ethanol and the potential (purity) for its recovery.

If the purity of the juice is high, above 85%, in São Paulo, for example, it means that the cane is ripe, clean, and healthy, and the pol % cane is also high. Other important indicators of the cane quality factor are fiber % cane (between 11% and 15%) and moisture % cane (between 68% and 72%). When analyzing sugarcane, it is important to be aware of the numerous variables that can impact results, regardless of the method of sampling, sample preparation, or analytical determinations.

Cane analysis

Whatever the method of cane analysis, the objective is always the same: to determine the pol % cane and the fiber % cane, together with the calculation of the juice purity (pol % brix). Approved sampling and analysis methods must have high reproducibility and repeatability.

For sugar plants also producing ethanol from process streams other than final molasses, as in Brazil, it is also necessary to determine the content of reducing sugars % cane and/or the total reducing sugars % cane. This is both for payment of the raw material by quality and for technological control of the industrial process. The moisture % cane can also be determined, as this helps in the interpretation of cane quality, as well as determinations of dextran, phosphates, starch, and other minor constituents of the cane juice.

In Brazil, the cane analysis results using the core/press method developed for cane payment have been used since years 1980s for sugar and

ethanol factory control, replacing the traditional methodology based on the fundamental equation as defined below.

The methods for evaluating the cane quality can be divided into two groups:

- Indirect analysis of cane
  - Fundamental equation "Milled cane + Imbibition water = Mixed juice + Bagasse"
  - First expressed juice (Australia, 5 and 3 coefficients; Java Ratio; Hawaiian Coefficient).
- Direct analysis of cane (DAC)
  - Cold extractor (wet disintegrator in South Africa) method.
  - Dry disintegrator plus hydraulic press method.

The main results obtained in the direct analysis of cane samples collected by the horizontal or oblique core sampler, analyzed by the press or extractor method, are the following:

- Fiber % cane
- Pol % cane
- Purity of the juice (press method)
- Purity of the cane (press and cold extractor method)

For mills that simultaneously produce sugar and ethanol (most commonly in Brazil), or distilleries that produce ethanol only, two other determinations make up the results of cane quality:

- Reducing sugars % cane (RS)
- Total reducing sugars % cane (TRS)

TRS can mean "Total Reducing Sugars" (see Chapter 5 "Stoichiometry" for more details), "Theoretical Recovery Sugar" in Louisiana USA, and "Total Recoverable Sugar", used in the Brazilian cane payment system

(ATR in Portuguese). This publication uses TRS only for "Total Reducing Sugars".

The cane laboratory equipment in Brazil (precision scales, refractometer, saccharimeter) must be connected to an electronic data collector and a bar code reader, which are interconnected by a wireless network and controlled by management software. The collectors automatically capture analysis results and other information via barcodes, such as sample code, analyst login code, and the date and time of sampling.

Considering the large number of samples collected daily, this relatively low-cost technology ensures greater reliability and security in recording the results from laboratory equipment.

7.1 Clean cane plus trash and soil material (gross cane)

During the process of cutting, loading, and transporting sugarcane, "extraneous matter" of vegetable origin ("trash") and dirt "soil" are carried into the industrial process.

Trash is a component of the raw material that cannot be used to produce sugar and ethanol, although a portion of it can be used for the cogeneration of electric energy. To facilitate this characterization, it is possible to distinguish "non-stalk" items:

- Green leaves formed by the leaf sheaths and leaf blades, including the coiled new leaf cartridge protecting the apical meristem and the immature internodes of the top of the cane.
- Partially dried or dead leaves, including leaf sheaths and blades.
- Rhizomes (underground part of the cane stool), and weeds brought with the cane during the harvesting process.
- Dirt and stones ("soil").

A better definition of all impurities must be "non-stalk" or, in the case of chopped harvested cane, "non-chopped stalk".

7.1.1 Fiber % cane

The sugarcane stalk is formed by fiber and absolute juice. **Fiber** is the solid portion of the cane (insoluble solids), and the **absolute juice** is the liquid portion formed by water (moisture), including "hygroscopic water" or "brix-free water", sugars (brix), and other soluble components.

Remembering:

$$\text{Absolute juice \% cane} = 100 - \text{Fiber \% cane}$$

$$\text{Moisture \% cane} + \text{Fiber \% cane} + \text{Brix \% cane} = 100\%$$

Several authors have widely discussed these concepts and some disagreements are ongoing.

When considering fiber % cane it is necessary to define the kind of material: clean whole stalk cane (net cane) or gross cane (raw cane feedstock material).

The fiber % cane, also known as "botanical fiber", can be measured by washing a sample of disintegrated cane in a tight weave cloth bag under running water, drying it until it reaches a consistent weight, and then reporting the weight percentage of the dry material as the fiber content. Although this method is not widely used, it can be employed in sugarcane variety breeding programs, where the entire stalk is manually cut and cleaned.

The "industrial fiber" is the denomination for samples collected with the core/sampler, which includes all the "non-stalk" components.

In Brazil, the result of fiber % cane by core/press can be classified according to the methodology of calculation:

Fiber % cane Tanimoto: The fiber calculated with the brix % juice extracted in the press, the wet bagasse weight, and the dry bagasse

weight, is known in Brazil as "Tanimoto fiber" (Tanimoto, 1964), described below.

Fiber % cane Consecana: In the Brazilian system for paying sugarcane by quality, field cane quality evaluation, and factory control, fiber is estimated based on the weight of wet bagasse in the press, without the need to determine the moisture content of the press bagasse.

7.1.2 Non-stalk materials in the cane feedstock

Delivering clean stalks for milling has become impractical with the advance of mechanized harvesting. In Brazil (conab.gov.br), 610 million tons of sugarcane (74 t/ha) were processed in 2022 in more than 400 mills. In São Paulo, the largest sugarcane-producing state, responsible for 212.9 million tons of cane in 2022, mechanized harvesting by chopper harvesters (Australian model) of cane without burning ("chopped green cane") reaches 90% of the cane supplied.

The survey of non-stalk material in the cane load was carried out by "manual dry cleaning" of samples of cane collected with the oblique or horizontal core sampling probe.

Note that all qualified and trained laboratory assistants can manually dry clean only 10 to 15 samples of chopped cane per eight hours of working day. This sampling is insufficient to represent the large amount of cane delivered for processing per day. The separation of non-billet stalk from cane samples is expert work and depends on the operator's training and dedication. Even so, the results are useful to keep the cane harvesting team alert for procedure improvements.

This influence of the "non-stalk" delivered with the cane from mechanized harvesting on the results of fiber % cane is complex. One of the advantages of the core/press method for analyzing the raw material for milling is that it handles this influence well. After the core/press method was adopted in the 1980s, in Brazil, doubts arose as to whether

the change in the fiber % cane of raw cane compared to clean cane was proportional to the percentage of non-stalks present in the load.

Experimental evidence of the non-stalk effect on fiber % cane values:

In the 2009/2010 harvest, a study was carried out in 18 sugar mills about the influence of non-stalk on the cane quality results with an oblique core sampler/press method. A total of 8071 samples were taken in the study (UNICA and ORPLANA, unpublished data).

Two near-identical samples were taken from each consignment. One sample was disintegrated as usual (gross cane), the other was hand-cleaned before disintegration, and the "non-chopped stalk" was weighed and expressed in kg/t of cane.

A subsample of disintegrated gross cane between 25 g and 100 g was used for ash determination by incineration, depending on the capsule size and the incinerator muffle's dimensions. These results were taken as the amount of soil in cane (kg/t of cane).

The fiber % gross cane or clean cane estimated based on the mass of wet bagasse cake from the press (using the Consecana-SP method) or calculated using the Tanimoto method (1964) for the core/press system exhibited a normal distribution (**Figure 7.1**).

In 92% of the data, the percentage of fiber in gross cane (whether determined by Consecana-SP or Tanimoto) falls between 10% and 16%. For the percentage of fiber in clean cane, using the Consecana-SP equation, 95% of the results range between 9% and 14%. When calculated with the Tanimoto method, 93% of the clean cane fiber results also fall within this range.

This pattern indicates that while the percentage of fiber in cane shows a wide variation, the majority of results are concentrated in a narrower range, regardless of the calculation method used, whether for gross cane or clean cane.

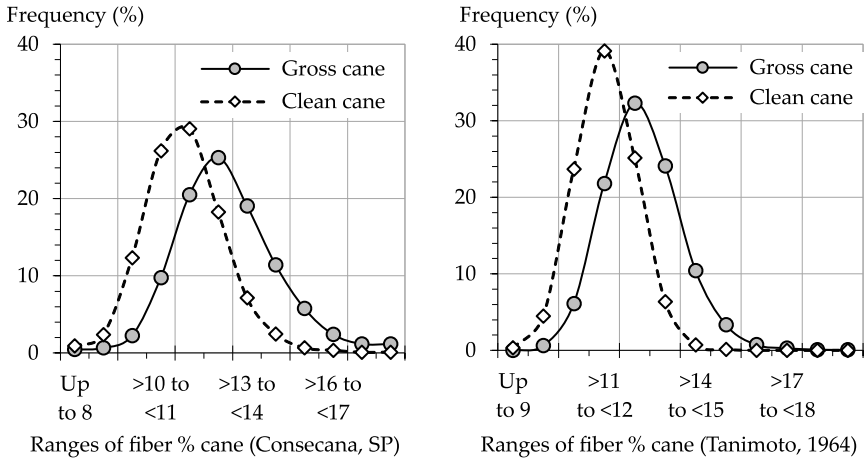

Figure 7.1 – Frequency distribution of fiber % cane calculated according to Consecana-SP (left) and Tanimoto (right). Data from 8071 core samples in the 2009/10 crop season in 18 Brazilian sugar mills.

Although some shipments of cane showed extremely high values of non-stalk material, 93% of the results for tops and dry trash from the 8071 samples were below 140 kg/t of cane. For the soil content in cane, the cumulative frequency showed that 92% of the samples were measured as below 35 kg of soil/t of cane (**Figure 7.2**).

7.2 The cold extractor method

The Brazilian "cold extractor" method, "wet disintegrator" or "cold digester" in Australia and South Africa, was developed in the 1950s, especially in Hawaii (Payne & Mahon, 1956), Australia (Foster, 1956), and South Africa (Buchanan & Brokensha, 1974) as a replacement technique for the hot digestion method (Norris). This method was initially developed to analyze the final bagasse of the mill or diffuser and later adapted for cane analysis (**Figure 7.3**).

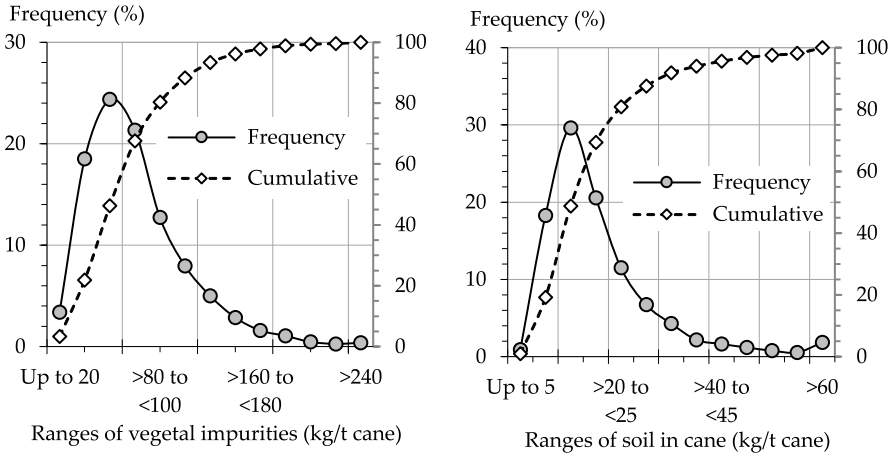

Figure 7.2 – Frequency distribution of vegetal impurities (left) and soil (right) on 8071 core samples in the 2009/10 crop season in 18 Brazilian sugar mills.

Figure 7.3 – Left - Brazilian model of cold extractor (wet disintegrator) for bagasse and cane analysis (Tecnal). Right - Australian model of the wet disintegrator (Jeffress). Images are not in the same scale.

The cold extractor or wet disintegrator is like an industrial blender with a stainless-steel bowl and a circulation of water around the bowl to keep the contents cool. A set of sharp hardened steel blades rotating at high speed inside the bowl processing a known mass of cane (around 500 g or 1000 g of cane, depending on the equipment model) and water (1000 g or 2000 g). After 20 minutes, the disintegration of the sample results in a mixture of finely disintegrated fiber and dilute juice. The diluted juice can then be separated for analysis and is called "extract".

The analysis of cane by the cold extractor method enables the determination of brix, pol, and fiber % cane without correction coefficients. It minimizes the influence of the sample preparation. Its main disadvantage is the longer time required to analyze each sample and the errors due to the high dilution of the cane sample.

Payne & Mahon (1956) considered that it is highly desirable, especially in experimental work, to get away from any method of evaluation of cane quality requiring arbitrary factors or coefficients and to arrive directly at pol % cane and fiber % cane. These are required in the Pol Ratio method, another method developed to analyze cane directly.

The ICUMSA wet disintegrator method GS5/7-1 (2011) for "The Determination of Pol (Polarization), Brix and Fibre in Cane and Bagasse by the Wet Disintegrator Method with Lead Subacetate – Official" is considered an official method for cane analysis. It is used extensively and as a routine procedure for cane payment only in South African mills Saranin (1986a). The lead acetate or subacetate clarifying agent has been banned in several countries, due to its high toxicity.

7.2.1 Deduction of formulas for cold extraction

Measured items in the cold extraction process

Cane sample: Mass of cane used in the cold extractor (g)
Added water: Mass of water used in the cold extractor (g)

Moisture % cane: Determined by drying a parallel disintegrated cane sample (100 g) at 110°C for 6:00 to 8:00 h.
Brix % extract: Refractometric brix of the extract (%)
Pol % extract = Saccharimeter reading of the extract ∗ (0.26065 - 0.000995 ∗ Brix % extract)

Total extract quantities

The mass of the "total extract" is formed by the "total absolute juice" of the cane sample and the water added to the bowl of the extractor. The mass quantities are:

Total cane water = Cane sample ∗ Moisture % cane / 100

Total brix = Total extract ∗ Brix % extract / 100

Total extract = Added water + Total cane water + Total brix

Replacing masses of "Total cane water" and "Total brix" and simplifying:

Total extract = Added water + Cane sample ∗ Moisture % cane / 100 + Total extract ∗ Brix % extract / 100

Total extract = (Added water + Cane sample ∗ Moisture % cane / 100) / (1 - Brix % extract / 100)

Brix % cane using moisture % cane

The total extract contains the total brix of the cane sample.

Brix % cane = Brix % extract ∗ Total extract / Cane sample

Substituting "Total extract" as previously deduced and simplifying, the equation for any ratio between Cane and Water used in the cold extractor method is obtained as:

Brix % cane = Brix % extract ∗ (Mass of added water / Mass of the Cane sample + Moisture % cane / 100) / (1- 0.01 ∗ Brix % extract)

Fiber % cane

Using the fundamental equation of sugar technology:

Fiber % cane = 100 - Moisture % cane - Brix % cane

Substituting the Brix % cane equation previously derived:

Fiber % cane = 100 - Moisture % cane - Brix % extract ∗ (Mass of added water / Mass of the Cane sample + Moisture % cane / 100) / (1 - 0.01 ∗ Brix % extract)

This results in the generic equation for calculating the fiber % cane using the cold extractor method:

Fiber % cane = (100 - Moisture % cane - Brix % extract ∗ (Mass of added water / Mass of the Cane sample + 1)) / (1 - 0.01 ∗ Brix % extract)

When the mass of the cane sample equals 500 g and that of added water equals 1000 g (or mL), the equation becomes:

Fiber % cane = (100 - Moisture % cane - 3 ∗ Brix % extract) / (1- 0.01 ∗ Brix % extract))

When the cane sample equals 500 g and added water equals 2000 g (or mL), the same equation becomes:

Fiber % cane = (100 - Moisture % cane - 5 ∗ Brix % extract) / (1- 0.01 ∗ Brix % extract))

Obs.: When using the exact mass of cane and water, factors 3 or 5 must be modified to their actual values.

Brix % cane

The total extract contains the total brix of the cane sample. Therefore the "brix % cane is that of the extract multiplied by the dilution ratio.

$$\text{Brix \% cane} = \text{Brix \% extract} * \text{Mass of total extract} / \text{Mass of the Cane sample}$$

The total extract can also be calculated by the sum of the water added to the extractor bowl with the total absolute juice (100 - fiber % cane) contained in the cane sample:

$$\text{Total extract} = \text{Added water} + (\text{Cane sample} - \text{Cane sample} * 0.01 * \text{Fiber \% cane}) \text{Total extract} = \text{Added water} + \text{Cane sample} * (1 - 0.01 * \text{Fiber \% cane})$$

Substituting this equation in the brix % cane formula shown above:

$$\text{Brix \% cane} = \text{Brix \% extract} * (\text{Added water} + \text{Cane sample} * (1 - 0.01 * \text{Fiber \% cane})) / \text{Cane sample}$$

The general formula for calculation of brix % cane with any proportion of Cane and Water in the cold extractor becomes:

$$\text{Brix \% cane} = \text{Brix \% extract} * ((\text{Added water} / \text{Cane sample} + 1) - 0.01 * \text{Fiber \% cane}))$$

When the cane sample equals 500 g and added water equals 1000 g (or mL), the previous equation becomes:

$$\text{Brix \% cane} = \text{Brix \% extract} * (3 - 0.01 * \text{Fiber \% cane})$$

For a cane sample of 500 g and added water of 2000 g (or mL), the same equation becomes:

$$\text{Brix \% cane} = \text{Brix \% extract} * (5 - 0.01 * \text{Fiber \% cane})$$

Pol % cane

The same reasoning applied to brix % cane can be used to deduce the formula for pol % cane.

$$\text{Pol \% cane} = \text{Pol \% extract} * ((\text{Added water} / \text{Cane sample} + 1) - 0.01 * \text{Fiber \% cane})$$

Using 500 g of prepared cane sample and adding 1000 g (or mL) of water the previous equation becomes:

$$\text{Pol \% cane} = \text{Pol \% extract} * (3 - 0.01 * \text{Fiber \% cane})$$

For a cane sample of 500 g and added water of 2000 g (or mL), the same equation becomes:

$$\text{Pol \% cane} = \text{Pol \% extract} * (5 - 0.01 * \text{Fiber \% cane})$$

Cane purity

In the cold extractor method, it is assumed that the purity of the cane is equal to the purity of the absolute juice, and, considering that all soluble solids pass into the extract, it is also equal to the purity of the extract.

$$\text{Cane purity} = 100 * \text{Pol \% cane} / \text{Brix \% cane}$$

The complication of "Brix-free water"

The "Brix-free water" or "Hygroscopic water" is defined as water strongly adsorbed in the cane fiber and unavailable for the dissolution of soluble components. It can only be driven off the fiber at elevated temperatures. If and when this exists, it is considered that analytical methods using the cold extractor (wet disintegrator technique) produce slightly higher pol and brix results than would be observed if all the water present in the cane fiber was available for the solution of soluble substances.

In the cold extractor method, the extract produced in the device remains in contact with the cane fiber. This can lead to moisture absorption, which may affect the concentration of Brix and pol in the extract. The author has been researching publications on Brix-free water for several years but has not found any reproducible studies supporting such water's existence. While the adsorption phenomenon is genuine, it does not justify the claimed fiber factor of 25%. Additionally, whole stalk cane that was traditionally hand-cut is not the same as chopped green cane harvested today using a chopper harvester. This difference requires scientific validation.

Although most researchers recognize the existence of hygroscopic water, only technologists in a few cane sugar industries (South Africa and Australia) apply it in the calculations of brix % cane and pol % cane. They usually consider that the "brix-free water" equals 25% of the fiber % cane. Their factories are also among the few that use the cold extractor method (wet disintegrator) for direct analysis of the cane sampled after preparation for crushing. In these cases, the factor 0.0125 is used instead of the 0.01 in the pol and brix % cane equations. For a subsample of 500 g of prepared cane sample and adding 1000 g (or mL) of water, the equations become:

$$\text{Brix \% cane} = \text{Brix \% extract} * ((\text{Added water} / \text{Cane sample} + 1) - 0.25 * 0.01 * \text{Fiber \% cane} - 0.01 * \text{Fiber \% cane})) = \text{Brix \% extract} * (3 - 0.0125 * \text{Fiber \% cane})$$

$$\text{Pol \% cane} = \text{Pol \% extract} * (3 - 0.0125 * \text{Fiber \% cane})$$

7.2.2 Cold extractor methods for cane analysis

The principle of the cold extraction method consists of the cold extraction of all the soluble constituents contained in the cane sample. In the dilute solution obtained (the extract), the brix and pol are determined.

Measuring "reducing sugars" and "total reducing sugars" is not typically carried out routinely due to the slow procedure and the highly diluted extract.

When the moisture content is determined in a parallel subsample the fiber % cane can be calculated, and all results obtained as a percent of cane. **Figure 7.4** shows a scheme for cane sampling and analysis using the cold extraction method.

The cane sample preparation for analysis in the cold extractor has less influence on the results than the press method. However, if the prepared cane contains very long fibers, the fibers can accumulate around the high-speed knives and the analysis may be compromised.

Cold extraction

For the Brazilian equipment, for finely prepared cane samples, a subsample of 500 $\pm$5 g of disintegrated cane sample with 1000 $\pm$10 g of water (1:3 dilution) can be used for samples of whole, unburned, clean, and freshly harvested cane.

When the cane contains a high level of trash (green and brown leaves and cane tops) or is poorly prepared, having long fibers and small pieces of cane (chips), a ratio of 500 g of disintegrated cane sample to 2000 g of water (1:5 dilution) should be used. This is generally the case when sampling prepared cane for milling.

Important: The exact mass of cane and water must be noted and the exact ratio of the added water + cane mixture to cane used in subsequent calculations.

The run time of the disintegrator can be a fixed value between 15 to 30 minutes, depending on the type of equipment and knives, sample preparation, and water-to-cane ratio (WCR). The cooling of the disintegrator bowl with cool running water is necessary, to reduce the

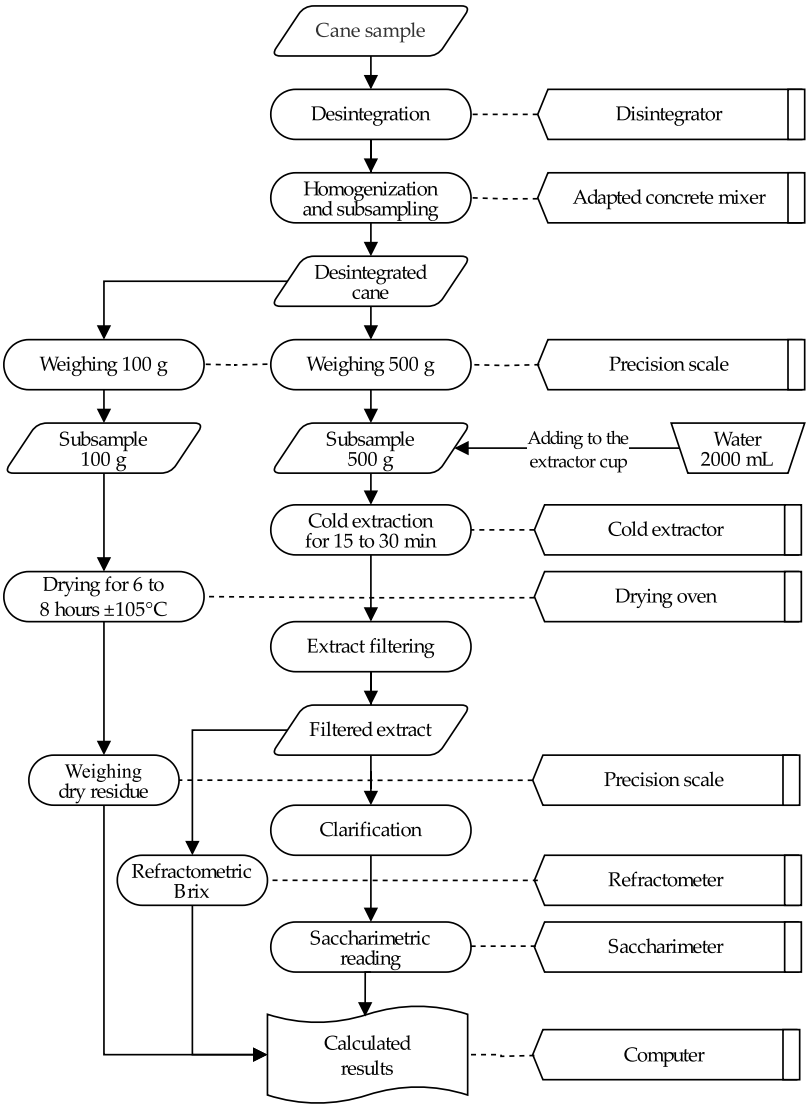

Figure 7.4 – Diagram of the cold extractor method for sugarcane analysis.

temperature of the cane mixture in the extractor bowl. This minimizes sucrose inversion and the destruction of sugars in the mixture.

Determination of moisture % cane

The moisture % cane should be determined directly in a parallel 100 g sample of disintegrated cane, by drying to constant mass in an oven with forced air circulation (with some fresh air replacement) at 105 °C. Drying time (usually between 6:00h to 8:00h) will depend on the type of oven, the air temperature, and the load on the oven. The mass loss so determined enables the calculation of the moisture % cane. When using the oven of the Spencer design, it is recommended that only a 50 g sample of the disintegrated sugarcane be taken and the calculation modified appropriately.

Analyses of the extract

Brix determinations and saccharimeter readings are carried out on the extract from the cold extraction. These require special care, as any errors will be multiplied by the dilution ratio, normally three (1:2 dilution) or five (1:4 dilution). For example, using 1:2 dilution the pol reading can range between 12 °Z to 28 °Z; and with 1:5 dilution the range will be narrow, from 7 °Z to 16 °Z.

Example of calculation of cane analysis by the cold extractor method

Cane analysis by the cold extractor method is used by some Brazilian sugar/ethanol mills parallel with the core/press technology, which is the official method for cane payment (Consecana).

The cold extractor result may also be used for factory control.

Recorded analysis data:

Cane mass in the extractor	502.1 g
Water mass in the extractor	1998.0 g

Saccharimeter reading	11.51 °Z
Brix % extract	3.50%
Moisture % cane*	69.24%
RS titration volume	35.24 mL
TRS titration volume	35.24 mL
Dil**	45 g/L

** Moisture % cane determined in a parallel sample. ** Extract dilution for TRS titration. Recommended: 30 to 60 g/1000 mL.*

Calculations:

Dilution ration = (Cane mass in the extractor + Water mass in the extractor) / Cane mass in the extractor
= (502.1 + 1998.0) / 502.1 = 4.9791

Pol % extract = Saccharimeter reading ∗ (0.26065 - 0.000995 ∗ Brix % extract)
= 11.51 ∗ (0.26065 - 0.000995 ∗ 3.5) = 2.96%

Fiber % cane = (100 - Moisture % cane - Dilution ratio ∗ Brix % extract) / (1 - 0.01 ∗ Brix % extract)
= (100 – 69.24 – 4.9791 ∗ 3.50) / (1 - 0.01 ∗ 3.50) = 13.82%

Brix % cane = Brix % extract ∗ (Dilution ratio - 0.01 ∗ Fiber % cane)
= 3.5 ∗ (4.9791 - 0.01 ∗ 13.82) = 16.94%

Pol % cane = Pol % extract ∗ (Dilution ratio - 0.01 ∗ Fiber % cane)
= 2.96 ∗ (4.9791 - 0.01 ∗ 13.82) = 14.33%

Cane purity = 100 ∗ Pol % cane/ Brix % cane
= 100 ∗ 14.33 / 16.94 = 84.6%

Extract density = $0.014236 * \text{Brix\% extract}^2 + 3.848468 * \text{Brix \% extract} + 997.159$
= $0.014236 * 3.5^2 + 3.848468 * 3.5 + 997.159 = 1010.803\ kg/m^3$

This cubic equation for extract density gives substantially the same result as the ICUMSA table for brix values between 0 to 12%.

Red. sugars % extract = (5209.6 - 262.5 ∗ (0.26 ∗ Saccharimeter reading)$^{1/3}$) / (RS titration volume ∗ (4.005 ∗ Brix% ex-tract + 996.759))
= (5209.6 - 262.5 ∗ (0.26 ∗ 11.51)$^{1/3}$)/ (32.44 ∗ (4.005 ∗ 3.5 + 996.759)) = 0.15%

Total Reducing sugars % extract = (10 / Dil) ∗ (496.4404 / TRS titration volume + 0.605)
= (10 / 45) ∗ (496.4404 / 35.24 + 0.605) = 3.26%

The equations above for "Reducing sugars % extract" and for "Total reducing sugar % extract" give the same result as Lane & Eynon's table (1922).

Reducing sugars % cane = Reducing sugars % extract ∗ (Dilution ratio - 0.01 ∗ Fiber % cane)
= 0.15 ∗ (4.9791 - 0.01 ∗ 13.82) = 0.73%

Total reducing sugars % cane = Total reducing sugars % extract ∗ (Dilution ratio - 0.01 ∗ Fiber % cane)
= 3.26 ∗ (4.9791 - 0.01 ∗ 13.82) = 15.78%

Purity TRS = 100 ∗ Total reducing sugars % cane / Brix % cane
= 100 ∗ 15.78 / 16.94 = 93.15%

RSC estimate = Total reducing sugars % cane - Pol % cane / 0.95
= 15.78 - 14.33 / 0.95 = 0.70%

TRS estimate = Pol % cane / 0.95 + Reducing sugars % cane
= 14.33 / 0.95 + 0.73 = 15.81%

Because the "total reducing sugars" determination in the extract is laborious and time-consuming, the previously estimated TRS % cane, based on pol % cane and reducing sugars % cane, is adequate and can be recommended for factory control.

Sucrose % cane (est.) = 0.95 * (Total reducing sugars % cane - Reducing sugars % cane)
= 0.95 * (15.78 - 0.73) = 14.30%

7.3 The hydraulic press method for analysis of cane

In the 1960s, technical studies began to be published on the use of a hydraulic press for extracting and analyzing cane juice, brix, and pol, and calculating fiber % cane. Main publications about the press method for cane analysis are Tanimoto (1964); Hoarau (1969); Lemaire (1971); Hugot (1974); Brokensha et al. (1976); Sturion (1977); Saranin (1986a) and others.

In Brazil, the ease and speed of the core sampler/press method for "direct analysis of cane" (DAC) compared with the usual methods at the time (fundamental equation or cold extractor), made the press procedure used routinely not only for cane quality payment system but also for industrial process control and agronomic management since the 1980s. This was due to the better statistical precision and speed of the results, leading to the feasibility of direct sampling and analysis of individualized loads of cane delivered for processing.

Compared to the wet disintegration (WD) method, which is time-consuming and requires expert personnel, the press method is faster and easier to use (Roussel, 2016). The results of both methods are highly correlated. The hydraulic press method has a lower standard error and is more repeatable for determinations of pol and fiber % cane. There is no significant difference in fiber % cane determinations between those made by the press method and by the reference WD method.

The results of cane analysis by the Near Infrared Spectroscopy (NIRS) method are improved when the calibration uses the hydraulic press method, which provides values for the pol, brix, and fiber % cane (Berding, 2010).

The Brazilian "hydraulic press method" (**Figure 7.5**) consists of pressing 500 g of shredded cane for one minute at a pressure of 250 kg/cm^2. Other heavier press models allow pressing 1000 g of cane with higher pressure and longer time.

The extraction of pol % pol in cane by the first mill in a milling tandem is around 75% to 80%, compared to the higher extraction of 84 to 85% achieved by the Brazilian cane press.

Figure 7.5 – Brazilian presses for cane analysis (under license from Pinette Emidecau, France).

Lemaire (1971) presents a complete description of the core-press method of cane analysis for the cane quality payment system and factory control, as adapted for Brazilian conditions (**Figure 7.6**).

Dry bagasse mass from the hydraulic press

In Brazil, the bagasse cake from pressing 500 g of shredded cane, containing the fiber and residual juice, is first weighed to obtain the "wet bagasse mass". The cake is manually broken up to facilitate drying and

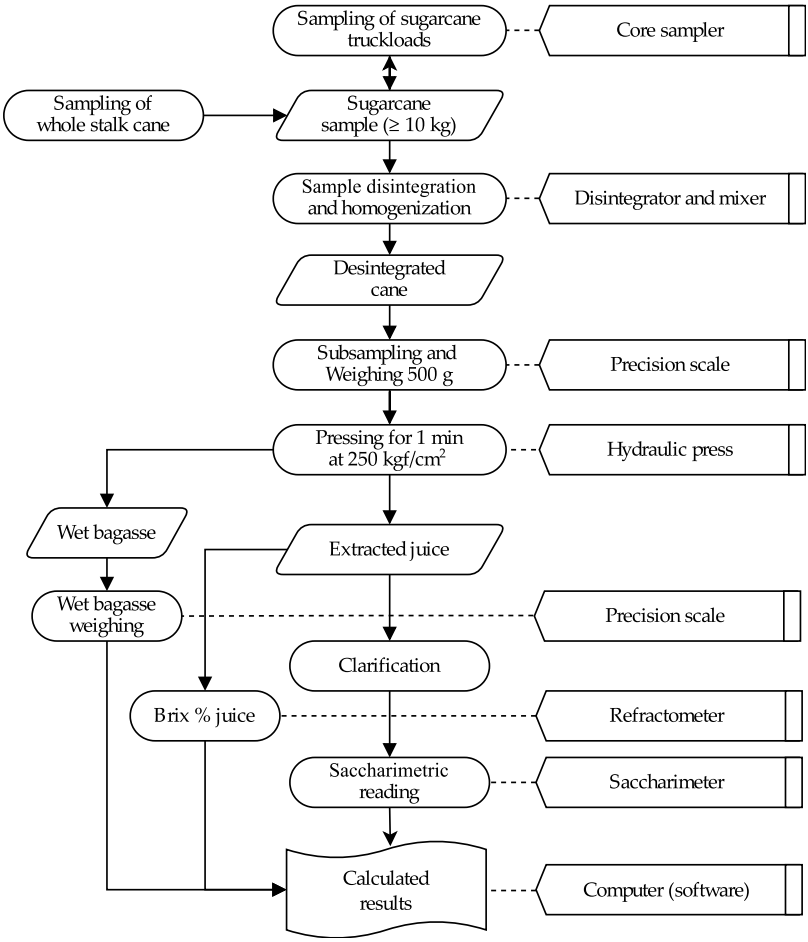

Figure 7.6 – Flow chart of the cane analysis by the hydraulic press method in Brazil.

then placed in an oven with forced air circulation (**Figure 7.7**) for eight to ten hours or until it achieves constant. The time taken depends on the type and size of the oven available.

Figure 7.7 – Large capacity oven with forced air circulation (with air refreshment) for drying hydraulic press cake.

In a 2009/10 harvest study, the pressing of 500 g of disintegrated cane at 250 kg/cm for 1.0 min., resulted in 148.5±1.7 g of wet bagasse with a moisture content % bagasse of 46.3±0.4%, coming from 8,071 loads in 18 factories. All the wet bagasse from the press was dried in a basket (20 cm x 15 cm x 10 cm) constructed with a perforated stainless screen sourced from a rotary vacuum mud filter (**Figure 7.8**).

Figure 7.8 – Basket built with a rotary vacuum filter screen for drying the press cake from 500 g of pressed cane.

Much of the soil carried with the cane during harvesting is retained in the bagasse after pressing the disintegrated subsample. This soil becomes part of the fiber % cane estimated according to the mass of wet bagasse in the press. To some extent, the same occurs with organic impurities (sugar cane tops, green leaves, partially dried or dried leaves, weeds, etc.).This causes some difficulty in interpreting the effects of the measured fiber in cane. The soil effect is significant, as soil is highly detrimental to the milling operation and the quality of the bagasse fed to the steam boilers of the factory.

In the aforementioned study, the moisture % bagasse had a mean value of 47%, with 91% of the results in the range of 41% to 52% (**Figure 7.9**).

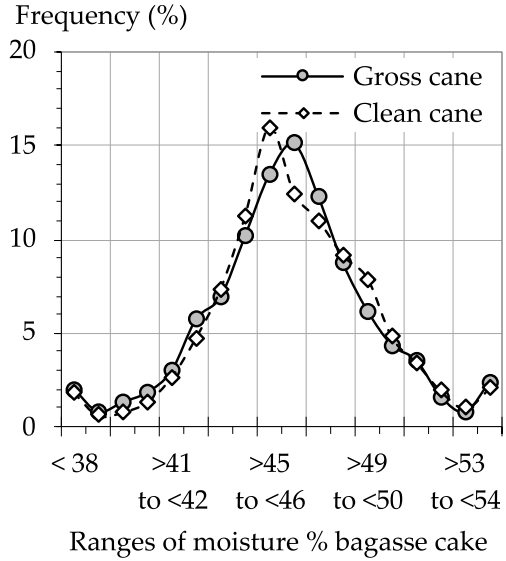

Figure 7.9 – Frequency distribution of moisture % bagasse press cake.

It is recommended that the full press cake be dried, as subdivision leads to a possible loss of material. After drying, the press cake sam-

ple is weighed to obtain the "dry bagasse cake mass" and a value for moisture % bagasse. It is important to determine or calculate the moisture % bagasse (official methods) in such a way that outliers can be identified.

7.3.1 Analysis of the extracted juice

Refractometric brix and pol are routinely determined in the juice extracted by the hydraulic press using traditional methods. Determinations are by near-infrared spectroscopy (NIRS) in some sugar factories.

Analysis of components of cane can include reducing sugars (RS), total reducing sugars (TRS), phosphorus, conductive ash, sugarcane nutrients (N, P, K, Ca, Mg), starch, pH, dextran, and acidity. Some of these determinations are not feasible in the cold extractor method as a routine, but they can be done while using the press method. This feature amounts to an advantage of the press method.

Density of the extracted juice

The density of the juice can be obtained from correspondence tables (ICUMSA, 1994) as a function of the refractometric brix % juice extracted in the press (Brix) or through the following quadratic regression equation:

$$\text{Juice density } (kg/m^3) = 0.015726 * \text{Brix}^2 + 3.81451 * \text{Brix} + 997.36$$

This equation is valid for the brix range between 5% and 26% which provides almost the same result to the third decimal place as the original ICUMSA table (1994). The suggested quadratic equation is ideal for use in spreadsheets and computer programs.

Expected saccharimeter reading

It is possible to test the consistency of the saccharimeter reading in a 200 mm tube using a regression equation as a function of the brix of the juice. Such equations are only indicated for checking the quality of laboratory data or for consistency testing in computer programs. It is recommended that each laboratory determines its equations, depending on the purity of the material analyzed and the working conditions.

Data from the analysis of whole, clean, well-stripped stalks sampled in a variety of competition trials made it possible to obtain the following equation:

$$\text{Expected saccharimeter reading} = -0.1246 * \text{Brix}^2 + 10.001 * \text{Brix} - 75.973$$

$R^2 = 0.9947$ in 314 pairs of data (This equation is presented only as an example)

According to the author's experience, the saccharimeter reading should not differ from the expected value by more than 5 °S.

Pol % juice

The pol % juice extracted by the press by direct determination in the clarified juice with no dilution (saccharimeter reading on a 200 mm tube) is calculated out by the equation:

$$\text{Pol \% juice} = 260 * \text{Saccharimeter reading} / \text{Juice density}$$

$$\text{Pol \% juice} = \text{Saccharimeter reading} * (0.26065 - 0.000995 * \text{Brix \% juice})$$

The result of this equation, valid for material with brix up to 26%, presents almost the same value as that obtained in the well-known official Schmitz table.

Note that for the Brazilian sugarcane payment system (CONSECANA, 2006), the saccharimeter readings carried out with a clarifying agent other than lead subacetate must be "corrected" using a specified linear regression equation.

Purity of the juice

Purity indicates the percentage of sucrose (pol) contained in soluble solids (Brix). The pol % cane and juice purity are the two most important indicators of the sugarcane's stage of maturation.

Juice purity =100 ∗ Pol % juice / Brix % juice

Note: The purity of the sugarcane juice is an important indicator of the quality of the raw material and should always be included in sugarcane analysis reports, together with the pol and moisture % cane.

7.3.2 Fiber % cane (Tanimoto, 1964)

The calculation of the fiber % cane by the press method became known in Brazil as the "Tanimoto method". Tanimoto (1964) presented calculations to obtain the fiber % cane by drying the cake from the press.

Similar calculations had already been formulated by (Turner & Rojas, 1962), who presented a "simple method for fiber determination" as an appendix to their work on cane deterioration after harvesting. These authors suggested grinding a sample of 30 to 50 kg at least twice in a laboratory mill or "extracting the juice by other equipment". Either the bagasse cake or the juice must be weighed, and the brix determined in the extracted juice. A subsample of bagasse should be used for oven drying. The sequence of calculations presented is the same as Tanimoto (1964).

Extracted juice

Mass of extracted juice = Mass of pressed cane - Wet bagasse mass

Residual juice

In every 100 g of extracted juice by the press, there are "100 - Brix % extracted juice" grams of water. Also, "Wet bagasse - Dry bagasse" evaluates the water content of the residual juice in the pressed cake, the mass of the residual juice in the cake from the press can be calculated using the brix of the extracted juice.

Thus:

Residual juice = 100 * (Wet bagasse cake mass - Dry bagasse cake mass) / (100 - Brix % extracted juice)

The mass difference due to drying the bagasse cake corresponds to the water content of the residual juice and the brix correction evaluates its soluble content. This interpretation of the residual juice is essential to understanding the fiber formula by the Tanimoto (1964) press method. This assumes that the brix of the extracted juice is equal to the brix of the residual juice. This assumption is strictly not true and this aspect needs more research.

Absolute juice

The absolute juice (hypothetically, all the cane juice, including "brix-free water") is formed by the juice extracted and the juice retained in the bagasse of the press: Absolute juice = Extracted juice + Residual juice

Replacing "Extracted juice" and "Residual juice", defined earlier:

Absolute juice = (Mass of pressed cane - Wet bagasse mass) + 100 * (Wet bagasse mass - Dry bagasse mass) / (100 - Brix % extracted juice)

Where the result of "Absolute juice" is contained in a specified mass of pressed cane, the absolute juice % cane will be given by:

Absolute juice % cane = 100 * Absolute juice / Mass of pressed cane

Sugarcane is made up simply of fiber (insoluble solids) and absolute juice (water plus soluble solids).

Replacing and simplifying:

Fiber % cane = (100 * Wet bagasse mass - Brix % juice * Dry bagasse mass) / (0.01 * Mass of pressed cane * (100 - Brix % juice))

Replacing the mass of pressed cane sample with 500 grams used in the procedure of fiber % cane Tanimoto (1964):

Fiber % cane = (100 * Wet bagasse mass - Brix % juice * Dry bagasse mass) / (5 * (100 - Brix % juice))

The correct value of brix to be used in this equation should be the brix % residual juice, which is unknown in routine analysis. An alternative would be introducing a correction factor to transform the brix % extracted juice into brix % residual juice. This correction might vary as a function of juice extraction and fiber content, under constant conditions of cane preparation, pressure, and pressing time. However, some experimental work has shown that the correction factor is very close or usually slightly greater than 1.0000 (one), and its use appears to be unnecessary. Further investigation should be carried out on this subject, including the evaluation of "brix-free-water".

The assumption that the extracted juice brix is equal to the residual juice brix does not result in a large deviation in the calculation of the fiber % cane. For example, if the wet bagasse mass equals 140 g, the dry bagasse mass is 80 g, and the brix % residual juice equals 19%, the fiber % cane would be 13.19%. Using the brix % extracted juice equal to 20%, the fiber content would be 13.00%, a difference of 1.44% in fiber % cane for a variation of one percentual point in the assumed brix.

7.3.3 Fiber % cane as a function of the wet bagasse mass % cane

The method known in Brazil as "Tanimoto fiber" can be used to pay for sugarcane by quality. However, the results obtained often do not correspond to expectations, due to the work involved in determining the considerable number of samples collected daily. This makes it desirable to use a linear regression equation for fiber % cane as a function of the wet bagasse mass of the press and the fiber % cane, and this has been done by several authors. This correlation used varies with the level of sugarcane preparation, the pressure level and pressing time, fiber content and type, etc.

When the analysis is performed in the Brazilian Consecana-SP cane payment system, there is no need to proceed with the drying of the bagasse from the press, as the fiber % cane is estimated by a linear regression equation as a function of the wet cake mass. The equation of linear regression calculated by Consecana-SP (2001) was developed by analyzing hundreds of samples under routine conditions with 500 g press samples:

$$\text{Fiber \% cane} = 0.08 * \text{Wet bagasse press mass} + 0.876$$

The equations obtained in different countries and regions cannot be compared, since each one was calculated under diverse conditions such as cane preparation, size of sample, type of press, pressure and pressing time, fiber content and type, etc. For example, in Australia, (Saranin, 1986b) found the equation:

$$\text{Fiber \% cane} = 3.5(\pm 2.0) + 0.035(\pm 0.002) * \text{Wet bagasse mass}$$

Where "Wet bagasse mass" is the cake mass of 1000 g of shredded cane.

Lemaire (1971), the first consultant to collaborate with Copersucar to study the sugarcane payment system based on quality in 1972, found the following linear regression equation between the mass of wet

bagasse (for 500 g cane samples in the press) and the fiber % cane (Tanimoto, 1964):

$$\text{Fiber \% cane} = 0.095 * \text{Wet press bagasse mass} + 0.4535$$

It is important to remember that it is not recommended to extrapolate results outside the limits of the equation's experimental range.

Effects of soil in the sample being pressed

During the pressing of the disintegrated cane sample, part of the soil carried with the cane during the harvest passes into the juice, and part is retained in the bagasse cake. An example of extracted juice colors from clean and dirty cane is shown in **Figure 7.10**.

Figure 7.10 – Juice extracted by the press from a clean cane sample and juice from a sample with soil).

As fiber % cane is estimated by the press method based on the mass of the bagasse after pressing, this soil becomes part of the fiber raw material, as will some of the trash formed by the green and dead leaves and the tops of the cane (**Figure 7.11**).

At the beginning of the studies and implementation of the core/press system in Brazil in the 1970s and 1980s, the possibility of determining the amount of soil in the juice extracted by the press and correcting the mass (g) of bagasse cake was discussed. However, although considered desirable, this procedure would be not feasible due to the large

Figure 7.11 – Different levels of the soil in the press cake (pressed bagasse). Press bagasse with an excess of soil (left). The most common bagasse after pressing (center). Pressed bagasse with high content of vegetable impurities (right).

number of samples collected daily at the plants, which could exceed 200 samples per 24 hours in three work shifts.

7.3.4 Pol % cane calculation (Hoarau, 1969)

A pioneering study by Hoarau (1969) demonstrated that the ratio of sucrose % absolute juice to sucrose % extracted juice is equivalent to the ratio of juice extraction to sucrose extraction, which he designated the "**c**" factor.

In his work, the "botanical" fiber % cane was determined by washing the sample from the wet disintegrator, placed in a special cloth bag, steeped in running water for two hours, squeezed manually six times, and then dried in an oven. This measure of cane fiber eliminates most of the soil loaded with the cane. It is lower than the "industrial fiber", obtained from the mass of wet bagasse and dry bagasse from the press, as this includes the "non-stalk" present in the cane sample, as performed by Lemaire (1971) and by Sturion & Fernandes (1975) at Copersucar Cane Lab in 1972.

If it were possible to extract all the absolute juice from the cane, the analysis of this juice would reveal the pol contained in the absolute juice, resulting in the simple formula:

$$\text{Pol \% cane} = \text{Pol \% absolute juice} * (1 - 0.01 * \text{Fiber \% cane})$$

As the pol of absolute juice is not known, it can be defined as equal to the pol of extracted juice multiplied by a transformation factor "c", and the equation becomes:

$$\text{Pol \% absolute juice} = \text{Pol \% juice} * c$$

$$c = \text{Pol \% absolute juice} / \text{Pol \% extracted juice}$$

From the Pol % cane equation cited before:

$$\text{Pol \% cane} = \text{Pol \% juice} * (1 - 0.01 * \text{Fiber \% cane}) * \mathbf{c}$$

The value of the coefficient "c" depends on the content and type of fiber in the cane, the degree and homogeneity of the crushing of the sample, the pressure and time of pressing, the type of equipment used, whether the cane is whole or chopped, etc. Practically, except for fiber content and type of equipment, the other interfering factors can be standardized, and it is possible to obtain a table of the "c" coefficients for different fiber content.

Several tables and linear regression equations of "c" as a function of fiber % cane have been published, specific to the situations in which they were obtained.

In the São Paulo sugarcane payment system by quality CONSECANA (2006), the value of "c" can be obtained by the equation:

$$c = (1.0313 - 0.00575 * \text{Fiber \% cane})$$

This equation, obtained experimentally (data not published or lost), modifies the calculation of pol % cane to:

$$\mathbf{\text{Pol \% cane} = \text{Pol \% juice} * (1 - 0.01 * \text{Fiber \% cane}) * (1.0313 - 0.00575 * \text{Fiber \% cane})}$$

7.3.5 Brix % cane calculation

The brix % cane is not usually reported value with the analysis of cane by the press method, brix being more commonly presented as its percentage of juice (brix % juice). However, it is a necessary result in some cases, such as for calculating the moisture % cane by the press method.

$$\text{Brix \% cane} = \text{Brix \% juice} * (1 - 0.01 * \text{Fiber \% cane})$$

Note that the calculation of the brix % cane does not use any coefficient such as "c", which is valid only for the pol. As the extraction of brix differs from the extraction of pol, the coefficient "c" cannot be used to calculate the brix % cane. Past work has shown that the coefficient "c1" (relation between the brix % absolute juice and the brix % juice extracted in the press) varies tightly around 1.000.

Saranin (1986a) found a significant correlation that resulted in the equation:

$$c1 = 1.01 - 0.008 * \text{Fiber \% cane}$$

For fiber % cane between 11% and 14%, the mean of c1 was equal to 0.960. Comparing the same range of fiber % cane, the mean of "c" (Pol % absolute juice / Pol % extracted juice) is equal to 0.9663.

While there is not enough research to evaluate the "c1" coefficient, it is recommended that it be assumed to be 1.00 and the brix % absolute juice be considered equal to the brix % of the juice extracted in the press.

The sum of brix, fiber, and moisture percentages on cane should always be 100. Thus, if the moisture % cane by direct analysis is known, then:

$$\text{Brix \% cane} = 100 - \text{Moisture \% cane} - \text{Fiber \% cane}.$$

7.3.6 Moisture % cane determination

The cane moisture can be determined directly by drying a sample of finally disintegrated cane (e.g. 50 g or 100 g), preferably in an oven with forced air circulation and air refreshment at 110 °C, until the constant mass is achieved.

As well it can also be calculated indirectly, as, knowing the fiber % cane and the brix % cane, the moisture % cane is obtained by:

Moisture % cane = 100 - Brix % cane - Fiber % cane.

It is important to measure or calculate the moisture % cane, as it may partially indicate the quality of the analytical results since mature sugarcane normally presents moisture percentage values between 68% and 72% (in the central south region of Brazil). When the value is below 66% it can indicate that the cane is going into drying stress, and if it is above 74% it indicates harvesting during wet weather or immature cane outside its ideal ripening point.

7.3.7 Reducing sugars determination

Although the reducing sugars (glucose and fructose) already present in the cane feedstock represent only 3% to 4% of the total reducing sugars in cane (TRS) after inversion, they must be measured separately in calculations of efficiency and losses in the manufacture of sugar and ethanol.

Reducing sugars % juice

Reducing sugars % juice can be determined analytically by the traditional method of Lane & Eynon (1923) or by chromatography. However, these methodologies have two drawbacks:

1. The large number of cane loads to be sampled daily makes it unfeasible to determine reducing sugars % juice in individual samples.

2. Experience has shown that, in a routine procedure, the analytical results differ from what is expected. The methods mentioned before are of high precision, but only when executed by well-trained expert technicians.

For these reasons, for factory control or cane payment, Brazilian mills prefer to use a linear regression equation to estimate reducing sugars % juice as a function of the purity of the juice.

The **first equation** for reducing sugars as a function of juice purity was obtained in 1998. It was based on data from analytical studies on 306 pairs of cane maturation samples conducted by the Copersucar Sugarcane Genetic Breeding Program (Fernandes, A.C.; nonpublished data; São Paulo, Brazil). The equation is:

$$\text{Reducing sugars \% juice} = 9.9408 - 0.1049 * \text{Juice purity}$$

In a later analytical study in 2001 with cane samples from 17 sugar mills, a **second equation** was established and has been used until the present time (2024 harvest). As yet, this study has not been published in a technical paper but, for sugar and ethanol plants that participate in the Consecana-SP system, the use of this equation is mandatory. The Consecana-SP equation is:

$$\text{Reducing sugars \% juice} = 3.641 - 0.0343 * \text{Juice purity}$$

Reducing sugars % cane

No published research has been found on the relationship between reducing sugars % extracted juice with reducing sugars % absolute juice. Thus, the same coefficient "c" for pol % cane is adopted by consensus, which means that the extraction of reducing sugars by the press is the same as the extraction of pol (apparent sucrose). This leads to the equation:

Reducing sugars % cane = Reducing sugars % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ (1.0313 - 0.00575 ∗ Fiber % cane)

7.3.8 Determination of the total reducing sugars (TRS)

Total reducing sugars % cane

When the total reducing sugars % juice (TRS) is known by direct analysis the TRS % cane can be obtained by:

TRS = Total reducing sugars % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ (1.0313 - 0.00575 ∗ Fiber % cane)

However, an indirect method is mostly more practical and, as inferred before in the calculation of reducing sugars % cane, it is assumed that the relationship between the pol % absolute juice and pol % extracted juice (ie. the coefficient "c") is equal to the ratio between the total reducing sugars % absolute juice and the total reducing sugars % extracted juice.

To date, no research proves the accuracy of this relationship. It is known that the coefficient for pol extraction is slightly different from brix extraction, but it appears that there is no known research on a coefficient to describe the behavior of total reducing sugars during press extraction.

Estimate of the total reducing sugars % cane

The exact determination of total reducing sugars % press juice by the Lane & Eynon method is considered impractical for the hundreds of samples collected daily in the sugarcane analysis laboratory by the core/press method. As an approximate indirect method and for medium and high-purity materials such as juice from mature cane, it is assumed that pol % cane is equal to sucrose % cane and that the complete inversion of 1 g of the sucrose adds 1/0.95 g of reducing

sugars. Thus, this is the TRS equation used by most Brazilian sugar and ethanol plants:

Total reducing sugars % cane = Pol % cane / 0.95 + Reducing sugars % cane

Direct determinations of relevant sugars by chromatography

Chromatographic techniques allow the direct determination of the individual sucrose, glucose, and fructose (all are fermentable sugars) in the juice extracted in the cane laboratory press, as well as some other components. These techniques enable the direct determination of the total fermentable sugars % juice:

Total fermentable sugars % juice = Sucrose / 0.95 + Glucose + Fructose

By substituting this into the approximate relationships used before we obtain an estimate of the total fermentable sugars % cane (TFS):

Total fermentable sugars % cane (TFS) = Total fermentable sugars % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ (1.0313 - 0.00575 ∗ Fiber % cane)

Note: The denomination of "total fermentable sugars % cane" (TFS) is used to differentiate it from "total reducing sugars % cane" (TRS) since the latter result uses the Lane-Eynon method which includes some non-fermentable reducing substances.

Other possible analytical determinations on juice

Several other determinations can be carried out on the extracted juice from the hydraulic press. They may include pH (must be preferably above 5.0), dextran, phosphorus (P_2O_5), starch, and ammoniacal and assimilable nitrogen.

However, these measurements should only be routinely requested if they provide interpretations that lead to changes in work procedures

resulting in improvements in product yields and efficiencies, or product quality.

7.4 Cane press method calculations example

Cane sample mass	500.00 g
Water bagasse mass	140.69 g
Saccharimeter reading (200 mm)	70.95 °Z
Brix % extract juice	19.70%

Juice density

The juice density (kg/m^3) can be obtained from the ICUMSA table or can be calculated using the following linear regression, valid for brix % juice between 5% and 26%.

$$\text{Juice density} = 0.015726 * \text{Brix \% juice}^2 + 3.81451 * \text{Brix \% juice} + 997.36$$
$$= 0.015726 * 19.70^2 + 3.81451 * 19.70 + 997.36 = 1078.6\ kg/m^3$$

Pol % juice

$$\text{Pol \% juice} = 1000 * \text{Saccharimeter reading} * \text{"0.26/Juice density } (kg/m^3)\text{"}$$

The ratio "0.26/juice density" is known as the "Schmidt Factor", which presents a highly significant linear regression as a function of the Brix % juice. Thus, the pol % juice can be calculated without reference to a table.

$$\text{Pol \% juice} = \text{Saccharimeter reading} * (0.2605 - 0.0009882 * \text{Brix \% juice})$$
$$= 70.95 * (0.2605 - 0.0009882 * 19.70) = 17.10\%$$

Juice purity

Juice purity = 100 * Pol % juice / Brix % juice
= 100 * 17.10/ 19.70 = 86.8%

The juice purity results should be expressed with one decimal place.

Fiber % cane

Using the equation of linear regression calculated by Consecana-SP for a 500 g cane sample:

Fiber % cane = 0.08 * Wet bagasse mass + 0.876
= 0.08 * 140.69 + 0.876 = 12.13%

Brix cane

Brix % cane = Brix % juice * (1 - 0.01 * Fiber % cane)
= 19.70 * (1 - 0.01 * 12.13) = 17.31%

This calculation assumes that the ratio of brix % absolute juice with brix % extracted juice (coefficient c1) is equal to 1.00.

Moisture % cane

Moisture % cane = 100 - Brix % cane - Fiber % cane
= 100 - 17.31 - 12.13 = 70.6%

This is an important sign of cane quality. When it is below 68% it can indicate that the plant has undergone drought stress and values above 72% occur with cane not fully mature.

Pol % cane

The pol % cane is calculated by the formula:

$$\text{Pol \% cane} = \text{Pol \% juice} * (1 - 0.01 * \text{Fiber \% cane}) * \mathbf{c}$$

Several tables of the coefficient "c" have been published, specific to the situations in which they were obtained. Currently, in the Consecana-SP cane payment system of São Paulo (Consecana-SP, 2006), the value of "c" must be obtained by:

$$c = (1.0313 - 0.00575 * \text{Fiber \% cane})$$

This equation simplifies the calculation of pol % cane to:

$$\text{Pol \% cane} = \text{Pol \% juice} * (1 - 0.01 * \text{Fiber \% cane}) * (1.0313 - 0.00575 * \text{Fiber \% cane})$$
$$= 17.10 * (1 - 0.01 * 12.13) * (1.0313 - 0.00575 * 12.13) = 14.45\%$$

Cane purity

$$\text{Cane purity} = 100 * \text{Pol \% cane} / \text{Brix \% cane}$$
$$= 100 * 14.45 / 17.31 = 83.5\%$$

Note that the purity of the cane (here 83.5%) is not identical to the purity of the juice (above 86.8%). This is because the extraction of brix (soluble solids) is not equal to the extraction of pol (sucrose).

Reducing sugars % juice

Applying the Consecana-SP equation for indirect estimation:

$$\text{Reducing sugars \% juice} = 3.641 - 0.0343 * \text{Juice purity}$$
$$= 3.641 - 0.0343 * 86.8 = 0.66\%$$

Reducing sugars % cane

Reducing sugars % cane = Reducing sugars % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ (1.0313 - 0.00575 ∗ Fiber % cane)
= 0.66 ∗ (1 - 0.01 ∗ 12.13) ∗ (1.0313 - 0.00575 ∗ 12.13) = 0.56%

Direct measurement of the total reducing sugars % cane (TRS)

When "total reducing sugars" (TRS) is directly determined in the extracted juice, the TRS % cane can be calculated by:

TRS = Total reducing sugars % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ (1.0313 - 0.00575 ∗ Fiber % cane)

Estimate of the total reducing sugars (TRS) % cane

Assuming that pol % cane is equal to sucrose % cane, Brazilian sugar mills apply the following equation to obtain an estimate of TRS % cane. This estimate is used for all the calculations involving factory control.

Total reducing sugars % cane = Pol % cane/ 0.95+ Reducing sugars % cane
= 14.45/ 0.95 + 0.56 = **15.77**%

7.5 Interpretation of cane analysis results

There is usually a great variation in the composition of the sugarcane feedstock throughout the season, as well as between seasons.

The two main indicators of cane quality are pol % cane and juice purity, and these two are often highly correlated. Lesser quality indications are the values of moisture % cane, fiber % cane, soil % cane, and trash % cane. High values of soil % cane are highly detrimental to milling train maintenance and to the operation of the bagasse boilers. High dextran levels are an indication of deterioration of the cane and are detrimental to the sugar crystallization operations.

Cane analysis results should be interpreted relatively, as is shown by the crop accumulated analytical results in the central-south region of Brazil for the main indicators of the cane quality (**Table 7.1**).

Each factory region must participate in benchmark programs to identify possible values outside the ordinary. Each company must define its limits and goals.

Table 7.1 – Recommendations (preliminary) for interpretation of the main results of sugarcane analysis, considering the accumulated crop means in the central-south region of Brazil.

Pol % cane		**Juice purity**	
>15%	Exceptional	>86%	Excellent
14 to 15%	Excellent	85 to 86%	Good
13 to 14%	Good	84 to 85%	Reasonable
12 to 13%	Bad	83 to 84%	Bad
<12%	Very low	<83%	Very low

Fiber % cane		**Moisture % cane**	
>14%	Very high	>71%	High
13 to 14%	High	70 to 71%	Normal
12 to 13%	Normal	69 to 70%	Normal Low
11 to 12%	Low	68 to 69%	Low
<11%	Very low	<68%	Very low

8 Cane evaluation in countries outside of Brazil

Different methodologies for sugarcane analysis are adopted in the various countries that produce industrial cane, either for payment to independent cane growers or for controlling field cane production and the sugar and ethanol industrial process.

Three cane analysis values are essential for factory process control: fiber % cane, pol % cane, and juice purity. In some countries, payment for cane from individual suppliers is based simply on the mass received with the fee based on the average quality of the mixed juice or the factory sugar yield.

Where payment of individual cane suppliers is by quality, each country uses a formula to estimate the sugar yield based on sampling from grouped adjacent deliveries from individual growers. Others, such as Brazil, use the core/press quality-based payments for each batch supplied and for factory control.

The procedures adopted in some countries are presented below, with examples of the calculations performed.

8.1 Réunion, France

In Réunion Island (France), the cane analysis by the press method is used for the cane quality payment system (CTICS, 2022) Centre Technique Interprofessionnel de la Canne et du Sucre ("Protocole campagne sucrière 2022").

Cane samples are cut into $\pm$10 cm billets, and crushed in a cutter-grinder, and approximately 1000 g of pulp is pressed at 200 bars pressure for one and a half minutes with a hydraulic press. Press cakes are weighed, and juice is collected.

Example, informed data

Disintegrated cane sample	1000.0 g
Wet bagasse mass	2528.0 g
Brix % juice (BJ)	18.0%
Pol volume by CTICS	803.45 g/cm^3

Example of calculated results

Poids specifique by CTICS = 1000 * (48 * 10-9 BJ^3 + 131 * 10^{-7} * BJ^2 + 38.552 * 10^{-4} * BJ + 0.99823 = 1072.15 kg/m^3

Saccharimeter reading (Pol volume / 0.26) = 63.08 °Z

A simple formula can give the same results as the ICUMSA Table developed for a range of brix from 10% to 26%.

Juice density or poids specifique (estimated) = 0.015726 * BJ^2 + 3.81451 *BJ + 997.36 = 1071.13 kg/m^3

Juice density from ICUMSA table = 1071.12 kg/m3

Pol % juice = 1000 * Pol volume by CTICS / Poids specifique
= 1000 * 16.4 / 1072.15 = 15.30%

The previous calculation can also be easily obtained by:

Pol % juice = Saccharimeter reading * (0.2605-0.0009882 * Brix % juice)
= 63.08 * (0.2605 - 0.0009882 * Brix % juice) = 15.31%

Juice purity = 100 * Pol % juice/ Brix % juice
= 100 * 15.31 / 18.0 = 85.1%

b = Wet bagasse mass / Disintegrated cane sample
= 252.0 / 1000 = 0.2520

Fiber is determined according to an equation established for the press method under Réunion Island conditions.

Fiber % cane = 0.55 * cake mass / pulp mass * 100

Where "cake" is the wet bagasse mass after pressure and "pulp" is the shredded cane sample.

Fiber % cane = 55 * Wet bagasse mass / Disintegrated cane sample
= 55 * 252.0 / 1000 = 13.86%

The extraction rate for the Emidecau press is given by:

Extraction = 1.012 - 0.41 * b = 1.012 - 0.41 * Wet bagasse mass / Disintegrated cane sample
= 1.012 - 0.41 * 252.0 / 1000 = 90.87%

The primary richness (R' or pol % cane) is defined by the equation:

R' = Pol % juice * (1 - b) / Extraction + 0.075

The coefficient +0.075 corresponds to the mean difference between the clarification filtration methods using lead subacetate and that with celite. The same principle is used in Brazil, but there the "correction" is applied to the saccharimeter reading (see Chapter 3 "General recommendations; Correction of saccharimeter reading") rather than to the pol % cane expression.

Replacing "b" and "Extraction" in the "R' primary richness", pol % cane is obtained by:

Pol % cane = Pol % juice * (1 - b) / (1.012 - 0.41 * b) + 0.075

b = Fiber % cane / 55

Pol % cane = Pol % juice * (1 - Fiber % cane / 55) / (1.012 - 0.41 * Fiber % cane / 55) + 0.075

Multiplying and dividing by absolute juice % cane and simplifying:

$$c = (1 - \text{Fiber \% cane} / 55) / ((1.012 - 0.41 * \text{Fiber \% cane} / 55) * (1 - 0.01 * \text{Fiber \% cane}))$$

$$\text{Pol \% cane} = \text{Pol \% juice} * (1 - \text{Fiber \% cane}/100) * \mathbf{c} + 0.075$$

With the coefficient "c" equation for CTISC, it is possible to create a table simulating the values of fiber % cane between 10% and 18% at intervals of 0.5 percentage points. From this simulated table, a linear regression was obtained by the author:

$$c = 1.01524 - 0.004378 * \text{Fiber \% cane} \ (R^2 = 0.9922)$$

This way, the pol % cane for CTISC can be calculated as:

$$\text{Pol \% cane} = \text{Pol \% juice} * (1 - 0.01 * \text{Fiber \% cane}) * (1.01524 - 0.004378 * \text{Fiber \% cane}) + 0.075$$

The results of pol % cane by the "c" coefficient equation are almost the same as the original CTITS formula, with small differences by 0.01 or 0.02 decimal points.

8.2 Australia

In Australia, the analysis of the first expressed juice in the first two milling rollers is used with an independent measure of fiber % cane, to calculate the cane quality results. The first expressed juice sample automatically time corresponds with a group of bin deliveries from the same grower. Cane for the fiber sample is sometimes taken to represent the variety of the delivery. The brix and pol % cane is calculated by the "5 and 3 factors**".** Dr. Kottman of the CSR company formulated these factors in around 1888 to estimate the pol, brix, and purity of cane from reading on the first expressed juice and an estimate of the fiber % cane.

In many Australian factories, the cane delivery is monitored by commercial NIRS devices such as the Direct Light NIR 6500 reflectance spectrophotometer (Foss NIRSystems Ltd.) scanning the prepared cane as it flows past a transparent widow in the feed chute to the first mill. The readings give instantaneous indications of cane quality values such as pol, brix, fiber, and soil. The readings require extensive calibration procedures to produce reliable results.

Fiber % cane in Australia

The fiber content of the cane, which is a non-juice material, comprises cane fibrous matter and dirt determined for each variety or group of varieties. In the Australian sugar industry, it used to be measured by sampling prepared cane, washing it in a special weave cotton fabric bag (bag method) free of dissolved solids, and drying it. It was quite labor-intensive, with manual bag-squeezing operations subject to variation among analysts. Its total processing time was 18 hours. There were issues with bag cloth consistency and the fact that some insoluble solids, particularly soil, were lost through the cloth.

Since the early 1990s, cane-fiber analysis has been mainly undertaken using the SRI can fiber machine. The washing procedure involved the initial recirculation of water through the sample in the can. This procedure returns all the soil and other insolubles into the mat and so the final washed mat retains almost all the soil. Since around 1999 some factories now use the NIR Cane Analysis System for online cane-fiber measurement, while the SRI can fiber machine is used daily for calibration purposes.

A new design of "cane fiber analyzer", labeled the Jefress CFA01, has been recently designed by Jeffress Ltd. to replace the SRI can fiber machine.

Method 4A of Sugar Research Australia (2014) was written specifically for the SRI cane fiber machine (**Figure 8.1**). The method also refers to

"Installation, operation and regular maintenance procedures as recommended in the instructions supplied by SRI" that "must be followed". The relevant SRI document is the "Instruction and operation manual for the 500 g can fiber machine".

Figure 8.1 – The SRI can fiber machine (Sugar Research Institute, 2021).

Brix % cane in Australia

Using the Kottman **3** factor for Brix % cane:

$$\text{Brix \% cane} = \text{Brix \% first expressed juice} * (100 - (\text{Fiber \% cane} + \mathbf{3})) / 100$$

Simplifying:

$$\text{Brix \% cane} = \text{Brix \% first expressed juice} * (0.97 - 0.01 * \text{Fiber \% cane})$$

Multiplying and dividing the previous formula by $(1 - 0.01 * \text{Fiber \% cane})$, the calculation of the coefficient that converts the brix % first expressed juice in brix % absolute juice ($\mathbf{c1_a}$) can be obtained by:

$$\text{Brix \% cane} = \text{Brix \% first expressed juice} * (1 - 0.01 * \text{Fiber \% cane}) * (0.97 - 0.01 * \text{Fiber \% cane}) / (1 - 0.01 * \text{Fiber \% cane})$$

Coefficient $c1_a = (0.97 - 0.01 * \text{Fiber \% cane}) / (1 - 0.01 * \text{Fiber \% cane})$

$$\text{Brix \% cane} = \text{Brix \% first expressed juice} * (1 - 0.01 * \text{Fiber \% cane}) * c1_a$$

For fiber % cane values between 11% to 16%, the coefficient $\mathbf{c1_a}$ is practically a constant (mean 0.9653), with a variation between 0.9663 and 0.9643. By accepting it as a constant 0.9653, the calculation of Brix % cane becomes:

$$\text{Brix \% cane} = \text{Brix \% first expressed juice} * (1 - 0.01 * \text{Fiber \% cane}) * \mathbf{0.9653}$$

Pol % cane in Australia

Using the Kottman **5** factor for pol % cane:

$$\text{Pol \% cane} = \text{Pol \% first expressed juice} * (100 - (\text{Fiber \% cane} + \mathbf{5})) / 100$$

Simplifying:

$$\text{Pol \% cane} = \text{Pol \% first expressed juice} * (0.95 - 0.01 * \text{Fiber \% cane})$$

Multiplying and dividing the above formula by (1 - 0.01 * fiber % cane), the calculation of the coefficient that converts the pol % first expressed juice in pol % absolute juice in Australia ($\mathbf{c_a}$) can be carried out by:

$$\text{Pol \% cane} = \text{Pol \% first expressed juice} * (1 - 0.01 * \text{Fiber \% cane}) * (0.95 - 0.01 * \text{Fiber \% cane}) / (1 - 0.01 * \text{Fiber \% cane})$$

$$\text{Pol \% cane} = \text{Pol \% first expressed juice} * (1 - 0.01 * \text{Fiber \% cane}) * c_a$$

To find the linear regression between the fiber % cane and the coefficient c_a, a table was created with fiber % cane values between 10% and 18% (intervals of 0.5%), and the values of the coefficient "c_a" were calculated with the expression:

$$c_a = (0.95 - 0.01 * \text{Fiber \% cane}) / (1 - 0.01 * \text{Fiber \% cane})$$

The linear regression between coefficient c_a and fiber % cane is:

$$c_a \text{ (factor 5)} = 0.95125 - 0.000674 * \text{Fiber \% cane} \quad (R^2 = 0.9987)$$

$$\text{Pol \% cane} = \text{Pol \% first expressed juice} * (1 - 0.01 * \text{Fiber \% cane}) * (0.95125 - 0.000674 * \text{Fiber \% cane})$$

For fiber % cane between 12% and 16%, the Australian coefficient (c_a) for the first expressed juice varies only between **0.9432** and **0.9405** with an amplitude of 0.0027 and a mean of **0.9419.**

These Australian results can be compared with the variation of the coefficient "c" of the Consecana-SP Brazilian core-press system, which is between 0.9623 and 0.9393 (mean 0.9508) for the same range of fiber % cane (12% and 16%), or by other authors (Hoarau, Mauritius 1969; Lemaire, Guadaloupe 1971; Hugot, Reunion 1974; Brokensha et al, South Africa 1976; Sturion, Brazil 1977; Saranin, Australia 1986b; Consecana, Brazil 2001; CTICS, Reunion 2022) who used the hydraulic press to extract the juice from the cane (**Figure 8.2**).

Accepting the calculations with factors 3 and 5 for the first expressed juice, the pol % cane using the Australian system can be obtained with sufficient accuracy by the formula:

$$\text{Pol \% cane} = \text{Pol \% first expressed juice} * (1 - 0.01 * \text{Fiber \% cane}) * 0.9419$$

This implies that:

$$\text{Pol \% absolute juice} = \text{Pol \% first expressed juice} * 0.9419$$

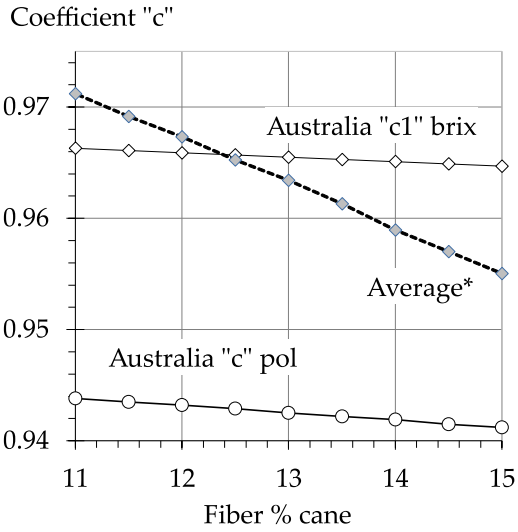

Figure 8.2 – Coefficient "c_a" (pol % absolute juice/ pol % first expressed juice) for Australian factor 5 and coefficient "c1" Australian factor 3 (brix % cane) compared to the average of coefficient "c" from eight different authors or regions.

The coefficient "c_a" cannot remain constant and should vary based on the percentage of fiber cane. Further investigation is needed.

The core-press system of sugarcane quality

In the early 1980s, an important contribution was made by Saranin (Saranin, 1986a, 1986b) to the implementation of the core/press system in Australia.

At the conditions of pressing adopted (1.0 kg of cutter-ground cane pressed at 25 MPa for 3 minutes), the mass of the wet fiber/plug for all commercial varieties of sugarcane was found to be close to 50% of the sample mass and this value was reproducible to $\pm$ 2.5 units, at 95% confidence limit, on a single measurement (Saranin, 1986a).

Fiber % cane = 0.50 ∗ Press plug % cane
c1 = Brix % absolute juice / Brix % press juice
c = Pol % absolute juice / Pol% press juice

Brix and pol were measured by wet disintegrator, and the following regression equations were established:

Brix coefficient c1 = 1.06 ($\pm$ 0.02) - 0.008 ($\pm$ 0.2) ∗ Fiber % cane

Pol coefficient c = 1.01 ($\pm$ 0.02) - 0.0035 ($\pm$ 0.2) ∗ Fiber % cane

For example, fiber % cane is 13.5%, coefficient

Brix coefficient c1 = 1.06 - 0.008 ∗ 13.5 = 0.952

Pol coefficient c =1.01 - 0.0035 ∗ 13.5 = 0.9628

The correlations are highly significant in both cases and fit 95% of the data within 0.05 units of **c1** and 0.03 units of **c**. (Saranin, 1986b) stated the coefficients obtained are within close range of those established by Hoarau (1969), Lemaire (1971), Brokensha et al. (1976), and Sturion (1977). Thus:

Brix % cane = Brix % press juice ∗ (1 - Fiber % cane / 100) ∗ (1.06 - 0.0080 ∗ Fiber % cane)

Pol % cane = Pol % press juice ∗ (1 - Fiber % cane / 100) ∗ (1.01 - 0.0035 ∗ Fiber % cane)

There is no evidence that the Saranin core/press system for cane payment was put into general practice in Australia, no doubt because of the lower costs of the traditional system based on first expressed juice sampling.

8.3 USA Louisiana

A version of the core/press method for cane analysis was introduced in Louisiana (USA) in 1976 (Rein, 2017). The juice of a prepared cane sample of 1000 g is extracted by hydraulic pressure at 25.3 MPa for two minutes and analyzed for brix and pol.

Calculations by Harold S. Birkett (1998)

The calculations below are based on the formulas of the technical article "Recommended Procedures for Core Sampling": Appendix - Birkett's Core Sampling Calculation Method (Birkett, 1998). The numerical example was taken from Sample 3. Some comments have been added based on these results. Some variable denominations were changed to the same nomenclature used in this book, and calculations were made in an MS-Excel® spreadsheet.

The following data is presented:

Pressed cane mass	1000.0 g
Wet press plug mass	420.3 g
Moisture % Wet press plug	51.56%
Sediment volume Brix % juice	18.3%
Pol % juice	15.8%
Sediment dry factor	0.302

Note: "Sediment dry factor" is a factor to convert the observed sediment volume % juice to dry sediment mass % juice. The "press plug" is often referred to as "bagasse" though it can be confused with the bagasse from factory milling.

Correcting the "Wet press plug mass"

Part of the soil carried with cane during harvest operation passes into the juice extracted with the hydraulic press. To correct this effect, a sediment test is carried out on the pressed juice using a lab centrifuge. The wet sediment volume % juice is converted to a mass of solids and

added back in fiber content calculation. It is assumed that the juice expressed has the same dissolved solids content as the juice remaining in the bagasse plug, an assumption which is not strictly true.

The additional residue weight is given by:

Dry sediment % juice = Sediment volume % juice * Sediment dry factor
= 10.0 * 0.302 = 3.02%

The mass of dry sediment in the juice is given by:

Mass of dry sediment in juice = (Pressed cane mass - Wet bagasse plug mass) * Dry sediment % juice / 100
= (1000 - 420.3) * 3.02 / 100 = 17.51 g

Extra residue mass = Dry sediment mass / (1 - Moisture % wet bagasse / 100)
= 17.51 / (1 - 51.56 / 100) = 36.15 g

This “extra residue mass” is added to the press plug mass and used to calculate the “Corrected wet press plug % cane”, for use in the core/press mass calculations.

Corrected wet press plug = Wet press plug + Extra residue
= 420.3 + 36.15 = 456.45 g

Corrected wet press plug % cane = 100 * Corrected wet bagasse / Pressed cane
= 100 * 456.45/1000 = 45.65%

Corrected dry press plug = Corrected wet press plug * (1 - Moisture % press plug / 100)
= 456.45 * (1 - 51.56/100) = 221.10 g

Author comment: Adding the sediment present in the press juice to the bagasse mass resulting from pressing is technically correct. However, executing this protocol as a routine step would incur extra costs and introduce another source of contention.

Calculations of the Fiber, Brix, and Pol % cane

Assuming that the extracted juice and residual juice have the same composition (Birkett, 1998), the "Fiber % Wet press plug" is given by:

Fiber % wet press plug = 100 - Moisture % wet press plug / (1 - Brix % juice / 100)
= 100 - 456.45 / (1 - 18.3/100) = 36.89%

Fiber % cane = Fiber % Corrected wet press plug ∗ Corrected wet press plug % cane / 100
= 36.89 ∗ 45.65/100 = 16.84%

Absolute juice % cane = 100 - Fiber % cane
= 100 - 16.84 = 83.16%

Brix % cane = Brix % juice ∗ Absolute juice % cane / 100
= 18.3 ∗ 83.16 / 100 = 15.22%

Pol % cane = Pol % juice ∗ Absolute juice % cane / 100
= 15.8 ∗ 83.16 / 100 = 13.14%

Cane purity = 100 ∗ Pol % cane / Brix % cane
= 100 ∗ 13.14 / 15.22 = 86.3%

Juice purity = 100 ∗ Pol % juice / Brix % juice
= 100 ∗ 15.8 / 18.3 = 86.3%

Comment: The purity of the extracted juice cannot be the same as the cane purity since the extraction of brix is not the same as pol or sucrose.

Moisture % cane = 100 - Fiber % cane - Brix % cane
= 100 - 16.84 - 15.22 = 67.94%

In São Paulo (Brazil) sugar mills, the mean of moisture % cane, calculated as before (Moisture % cane = 100 - Fiber % cane - Brix % cane), is 70.5% ($\pm$0.8%) for the crops between 2006/07 to 2015/2016 (Source: Consecana-SP, private information).

Using the fibraque correction

A revised core/press method formula was introduced in 1998 in Louisiana sugar factories (Birkett & Stein, 2007; and Legendre, 2010) including a correction for fiber to allow for "brix-free" water. No recent information was published or found about this matter.

Fiber corrected to fibraque ("New Fiber") = Fiber $*$ 1.30

Comment: Quoted from Rein, 2007: "In 1998 a correction supposing Brix-free water of 30 % (rather than the more common 25% value) was incorporated to give a pol content in the cane that agreed with the direct analysis. It is called a fibraque correction and leads to more satisfactory results". This statement is not mentioned in the original paper (Birkett, 1998) or others.

A **Z factor** to correct extracted juice brix to absolute juice brix was introduced in 1998 in Louisiana sugar factories. This Z factor corrects the brix % extracted juice to brix % absolute juice as applied to the calculation of brix % cane.

The following calculations should be used:

Z = 1.15 - 0.00018 $*$ (1000 - Corrected wet press plug mass)
= 1.15 - 0.00018 $*$ (1000 - 456.45) = 1.0522

Comment: "The correction factor Z is empirically derived to give an absolute juice purity close to the value measured by direct analysis, and it is a weak function of residue" (Rein, 2007).

New Fiber % cane = Fiber % cane * 1.30 = 21.89%

Comment: The concept of hygroscopic water, or brix-free water does not mean an increase in cane fiber percentage, but rather a reduction in the absolute juice volume.

New Brix % cane = Brix % cane * (100 - New Fiber % cane) / (100 - Fiber % cane) * Z
= 13.14 * (100 - 21.89) / (100 - 16.84) * 1.0522 = 15.04%

New Pol % cane = Pol % cane * (100 - New Fiber % cane) / (100 - Fiber % cane)
= 13.14 * (100 - 21.89)/(100 - 16.84) = 12.34%

New purity of cane = 100 * New Pol % cane/ New brix % cane
= 100 * 12.34/ 15.04 = 82.05%

New moisture % cane = 100 - New Fiber % cane - New brix % cane
= 100 - 21.89 - 15.04 = 63.07%

Comment: This example's result of moisture % cane (63.07%) is technically unrealistic (too low). It seems that the "New Fiber % cane" (fibraque) should not be used in calculations.

Alternative calculation for pol % cane in Louisiana

The calculations presented in this item are not from the technical papers of Birkett & Stein (2007) or Legendre (2010). The objective is a tentative study of using their formulas in similar concepts as Hoarau (1969), i.e., the coefficient "c".

According to the traditional equations of the sugar industry, the cane is made up of fiber and absolute juice. In percentage of cane:

Absolute juice + Fiber = 100

The following calculations recognize hygroscopic water as 30% of the fiber, as used in Louisiana sugar mills (Birkett, 1998 and Rein, 2007).

Assuming that the brix-free water is equal to 30% of the fiber % cane:

Absolute juice = 100 - 0.30 * Fiber % cane - Fiber % cane = 100 - 1.30 * Fiber % cane

Example calculation with the before listed data:

Fiber % cane	16.84%
Brix % juice	18.3%
Pol % juice	15.8%

Absolute juice % cane = 100 - Fiber % cane = 83.16%

The pol % cane is obtained by:

Pol % cane = Pol % juice * (100 - 1.30 * Fiber % cane) / 100
= 15.8 * (1 - 0.0130 * 16.84) = 12.34%

This is the same result of the New Pol % cane found before (Birkett, 1998).

Considering the methodology of calculation described by Hoarau (1969):

Pol % cane = Pol % juice * (1 - 0.01 * Fiber % cane) * **c**

c = (100 - 1.3 * Fiber % cane) / (100 - Fiber % cane)

A linear regression for Louisiana coefficient "**c**" was obtained simulating results for fiber % cane from 10% to 18% versus coefficient "c" calculated with the last equation.

c = 1.00773 - 0.00406 * Fiber % cane (R2= 0.9993)

This way, the pol % cane for Louisiana sugar mills can be written as:

Pol % cane = Pol % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ (1.00773 -0.00406 ∗ Fiber % cane)
= 15.8 ∗ (1 -0.01 ∗ 16.84) ∗ (1.00773 -0.00406 ∗ 16.84) = 12.34%

Brazilian core/press method

For comparison purposes, the following results will be obtained by applying the same values to the Brazilian cane payment system formulas (Consecana/SP).

Wet bagasse mass (no sediment correction)	420.3 g
Dry bagasse mass (no sediment correction)	203.59 g
Brix % juice (informed)	18.3%
Pol % juice (informed)	15.8%

There is no sediment correction in the Consecana/SP (Brazil):

Fiber % cane = (100 ∗ Dry press plug - Wet press plug ∗ Brix % juice) / (10 ∗ (100 - Brix % juice))
= (100 ∗ 203.59 - 420.3 ∗ 18.3) / (10 ∗ (100 - 18.3)) = 15.50%

Absolute juice % cane = 100 - Fiber % cane
= 100 - 15.50 = 84.50%

In the Consecana system, there is no "c1" coefficient:

Brix % cane = Brix % juice ∗ (1 - 0.01 ∗ Fiber % cane)
= 18.3 ∗ (1 - 0.01 ∗ 15.50) = 15.46%

The coefficient "c" used here is from Consecana/SP:

Pol % cane = Pol % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ (1.0313 - 0.00575 ∗ Fiber % cane)
= 15.8 ∗ (1 - 0.01 ∗ 15.50) ∗ (1.0313 - 0.00575 ∗ 15.50) = 12.58%

Cane purity = 100 ∗ Pol % cane / Brix % cane
= 100 ∗ 12.58/ 15.46 = 81.37%

Moisture % cane = 100 - Fiber % cane - Brix % cane
= 100 - 15.50 - 15.46 = 69.04%

8.4 South Africa

The 14 sugar mills in South Africa are the only ones that routinely use the prepared cane (for milling or diffusion) for analysis by the wet disintegrator method. This is termed Direct Analysis of Cane (DAC) and is preferred, though several studies and research, including work in South Africa country (Brokensha et al., 1976), have demonstrated the advantages of the core/press method.

The DAC method for cane analysis is used for the cane payment system and also for factory control, where it is applied to the "mill balance" following the fundamental equation "Cane + Imbibition water = Mixed juice + Final bagasse".

For the DAC the "Laboratory Manual for South African Sugar Factories" (SASTA, 2009) recommends using 1000 ±10 g of the prepared cane sample with 2000 ±10 g of water from a cold water dispenser. A wider tolerance (±10 g) is permitted as the computer calculation system uses the actual mass recorded. Note that the South African wet disintegrator equipment is larger than the Brazilian cold extractor model.

The DAC procedure is generally regarded as the most accurate method for the analysis of cane (Rein, 2017). This is true when comparing the results from the same sample analyzed by the core/press methods. However, DAC costs for the cane supplier would surely be higher than for the core/press method. A cane lab with an oblique sampler, a pair of forage-type disintegrators (one on standby), a hydraulic press, and three analysts per shift (four in the daytime) can analyze around 250 samples per 24 hours. For this level of sampling, at least five large-capacity wet disintegrators are required for DAC, and the operation of these would require more technicians and higher costs.

Calculations with the wet disintegrator (SASTA)

South African mills work with 1000 g of cane sample diluted with 2000 g of water for 20 minutes, using a larger wet disintegrator than the Brazilian model. The SASTA calculation formula considers the influence of "Brix-free water" or "hygroscopic water", assumed to be 25% on dry fiber.

Fiber % cane = (100 - Moisture % cane - **3** ∗ Brix % extract) / (1- 0.01**25** ∗ Brix % extract))

Brix % cane = Brix % extract ∗ (**3** - 0.01**25** ∗ Fiber % cane)

Pol % cane = Pol % extract ∗ (**3** - 0.01**25** ∗ Fiber % cane)

The coefficient "3" in these equations relates to the dilution "(1000 g of cane + 2000 g of water)/ 1000 g of cane".

São Paulo, Brazil, and South African sugar mills

The latitude line at 23° south runs through three major sugarcane-producing regions in South Africa, Australia, and Brazil. However, those areas differ in terms of climate, soil type, topography, the size of the blocks used for cane cultivation, and the sugar technology used in the factories. Hence, the comparison provided in **Table 8.1** below is only superficial.

Although the conditions are quite different in South Africa compared to São Paulo, as previously highlighted, the results of the cane analysis are very close, except for the fiber % cane. The fiber was 2.1 points higher in South Africa, which is reflected in the result of moisture % cane. This information needs a better investigation and discussion and the inclusion of other regions or countries.

Table 8.1 – Arithmetic means obtained in 14 South African sugar mills, and results of São Paulo sugar and ethanol mills. Cane sampling and analysis: South Africa uses a prepared cane and wet disintegrator, and São Paulo works with a core/press system.

Region	**South Africa**	**São Paulo**	**Diff.**
Crops period	2001-2017	2006-2015	%
Harvest crops	17 crops	10 crops	
Milled cane*	18.7	333.5	1683
Fiber % cane	15.0	12.9	**-14.5**
Brix % cane	16.0	16.7	4.3
Pol % cane	13.5	13.7	2.2
Moisture % cane	69.0	70.5	2.2
Cane app. purity	84.2	82.5	-2.0
Juice app. purity (a)	85.3	86.0	0.8
RS % juice (b)	0.52	0.69	32.7
RS % cane (c)	0.42	0.58	38.1
TRS % cane (d)	14.7	15.0	2.4

Notes:
* Mean per harvest season (million tons of cane/year)
South Africa:
(a) Mixed juice apparent purity (adj.)
(b) (Glucose + Fructose) % mixed juice
(c) (Glucose + Fructose) % cane
(d) (Sucrose/0.95 + Glucose + Fructose) % cane
São Paulo:
(a) Extracted juice apparent purity
(b) RS % press juice (est.)
(c) RS % cane (est.)
(d) TRS % cane (est.)

Estimates (est.):
Reducing sugars % press juice = 3.641 - 0.0343 * Juice purity
Reducing sugars % cane = RS % juice * (1 - 0.01 * Fiber % cane)
* (1.0313 - 0.00575 * Fiber % cane)
Total reducing sugars % cane = Pol % cane/ 0.95 + Reducing sugars % cane

The press method by Brokensha et al. (1976)

A comprehensive study of the press method was performed in South Africa by Brokensha, M.A.; King, S. & Lamusse, J.P. in the early seventies. The presumed methodology and main results are described below.

Objectives of the Brokensha et al study:

1. Formulation of general equations for the relating press cake mass % cane sample mass to the fiber % cane, and the evaluation of the c and c1 coefficients for South African conditions.
2. Investigation into the effect of soil and trash on the "fiber by press" results.
3. Investigation to determine the effect of variations in cane preparation on the "fiber by press" results.

In the Brokensha et al. (1976) study, a sample of prepared cane taken from the mill carrier after passing the cane knives and mill shredder was further prepared in a laboratory shredder.

A 1000 g subsample was transferred to the perforated cylinder of the hydraulic press. A pressure of 268 kg/cm^2 was applied for 4 minutes. The collected press juice was analyzed for pol and brix by refractometer. A subsample of the bagasse plug from the press was analyzed by the wet disintegrator method (200 g of plug and 2000 g of water).

The pol and brix content were determined on the extract. The moisture content was determined on another subsample of the bagasse plug. In parallel with each of the prepared cane samples, a second sample was analyzed for pol, brix, and fiber % cane by the DAC wet disintegrator method (**Table 8.2**).

Table 8.2 – Varieties, fiber % cane, and standard deviation (SD) for unburnt trashed (T) and burnt cane (B).

Factors	All samples	NCo 376 trashed	NCo 376 burnt	N55/805 trashed
Samples	104	51	14	22
Fiber % cane	15.45	15.82	14.26	15.67
$\pm$ SD	1.64	1.86	1.72	0.89

Regression equations relating press cake mass to fiber % cane (via fiber % press cake)

One of the advantages of the press method is the possibility of estimating the fiber % cane as a function of the mass of wet bagasse plug (g) from the press on the 1000 g cane samples (**Table 8.3**). However, linear regression is highly influenced by several factors and must be used in the same conditions of the trial.

Table 8.3 – Linear regression equation (Fiber % cane = a + b $*$ Wet bagasse mass) and example calculated values for three levels of "Wet bagasse mass (g)" for trashed unburnt (T) and burnt cane (B).

Factors	All samples	NCo 376 trashed	NCo 376 burnt	N55/805 trashed
a	1.48	-0.37	1.70	6.42
b	0.0420	0.0477	0.0415	0.0270
R^2	0.8464	0.8836	0.8836	0.6561
Fiber % cane		**Pol % cane**		
250g	12.0	11.6	12.1	13.2
320g	14.9	14.9	15.0	15.1
390g	17.9	18.2	17.9	17.0

These results show a difference in fiber % cane at each extreme of wet bagasse plug mass (**Figure 8.3**), except for N55/805 T, which has a lower slope and lower R^2 value.

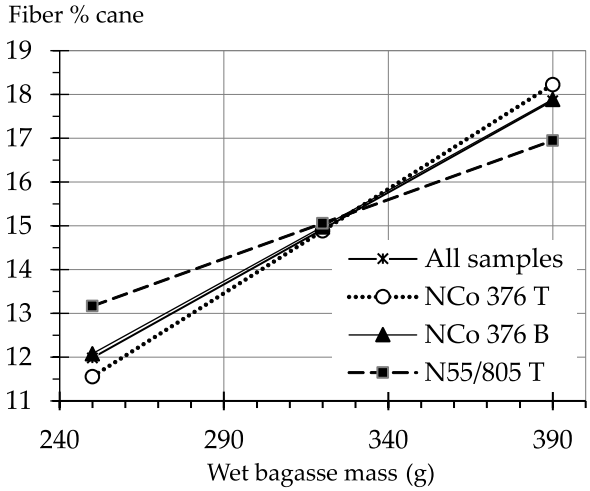

Figure 8.3 – Linear regression of fiber % cane against the mass of the wet press bagasse for trashed (T) and burnt cane (B).

Linear regression Coefficient "c" versus Fiber % cane

Coefficient "c" can be obtained by linear regression as a function of fiber % cane to calculate the pol % cane from the measured value of pol % mixed juice:

Pol % cane = Pol % juice ∗ (1 - 0.01 ∗ Fiber % cane) ∗ **c**.

In this case, the regression coefficient (R^2) for pol % cane as a function of pol % juice and fiber % cane was lower than that obtained for fiber % cane against wet press bagasse mass and insignificant for N55/805 T (R^2= 0.0324), which prevents any comment for the latter variety (**Table 8.4**).

Table 8.4 – Linear regression equation and simulation for three levels of wet bagasse plug mass fixing the pol % juice value as 16.5%.

Factors	All samples	NCo 376 trashed	NCo 376 burnt	N55/805 trashed
a	1.0508	1.0456	1.0822	0.9865
b	-0.006543	-0.006181	-0.008601	-0.002499
R^2	0.4761	0.5625	0.6724	0.0324
Fiber % cane		**Pol % cane**		
11.0	14.4	14.4	14.5	14.1
14.5	13.5	13.5	13.5	13.4
18.0	12.6	12.6	12.6	12.7

However, although the estimated results for the "c" coefficient are different for each equation (**Figure 8.4**), the results for pol % cane are the same up to the first decimal place, except again for the N55/805 T variety.

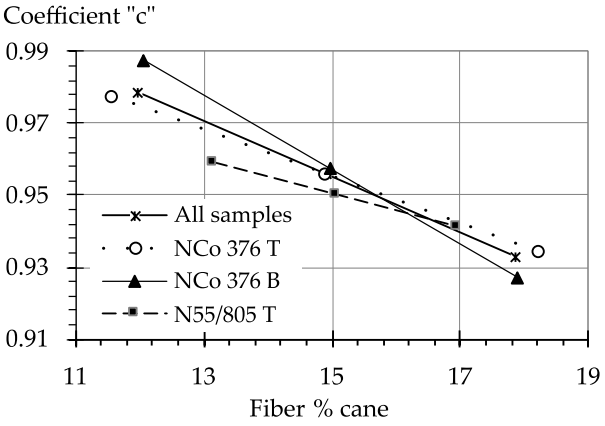

Figure 8.4 – Linear regression between coefficient "c" against trashed (T) and burnt cane (B) and three cane varieties.

The limited range of fiber encountered in the tests has been a real issue and this has contributed to the poor correlations. Similar to the relationship between the fiber % cane and the mass of the press bagasse, there are variations in the slope for different cane categories. These variations appear to limit the practical implementation of the press method.

Upon reviewing the data presented by Brokensha et al. (1976), it appears that there is valid data only for the NCo 376 variety.

Linear regression Coefficient "c1" versus Fiber % cane

Poor correlations were found between the ratio of brix % absolute juice to brix % press juice (Coefficient c1) and the fiber % cane.

The results of the "c1" coefficient from Brokensha *et al* (1976) show differences between the four equations, however, R^2 below 0.2 indicates that they are non-significant values. This invalidates any conclusion about the "c1" coefficient.

8.5 General results comparison for cane analysis

Purity of extract juice and absolute juice

When the cane is pressed, the initial portion of extract juice comes primarily from the parenchyma cells, which are specialized for storing sucrose. This juice tends to have a higher purity because it contains more of the desired sugar compounds. As pressing continues or pressure increases, the xylem cells, which contain water and nutrients, also rupture. This leads to a dilution of the purity of the extracted juice, as more non-sucrose components are released into the mix as demonstrated by Douwes-Dekker (1961) at SMRI, in South Africa **Figure 8.5**.

The first portions of extract juice typically have a higher apparent (and true) purity than do later portions of extract juice. The pol % residual

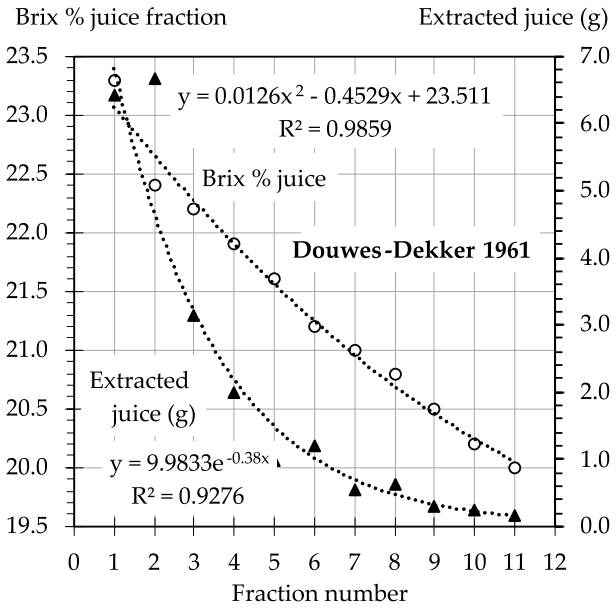

Figure 8.5 – Distribution of brix and mass of extract fractions while pressing shredded cane with increasing static pressure (Douwes-Dekker, 1961).

juice is lower due to dilution with other xylem fluids. So, the pol % extracted juice is greater than the pol % absolute juice.

Coefficient "c" as determined in all studies

Several authors have studied the relationship between pol % absolute juice with pol % extracted juice by the press (coefficient "c") under different working conditions. Details were discussed in Section 7.3.4 concerning Hoarau (1969) (**Table 8.5**).

Table 8.5 – The coefficients of linear regression for equations of the coefficient "c" obtained by several authors and different methodologies ($c = b + a * FC$) where FC = Fiber % cane are presented bellow.

Coefficient "c" by the core/press method

1 Hoarau (1969)	$c = 1.0093 - 0.00348 * FC$	(R2= 0.9969)
2 Lemaire (1971)	$c = 1.01439 - 0.00273 * FC$	(R2= 0.9982)
3 Hugot (1974)	$c = 1.00736 - 0.00386 * FC$	(R2= 0.9994)
4 Brokensha (1976)	$c = 1.0508 - 0.006543 * FC$	
5 Sturion (1977)	$c = 0.99678 - 0.0029 * FC$	(R2= 0.9878)
6 Saranin (1986b)	$c = 1.01 - 0.0035 * FC$	
7 Consecana (2001)	$c = 1.0313 - 0.00575 * FC$	
8 CTICS (2022)	$c = 1.01524 - 0.00438 * FC$	(R2= 0.9922)
9 Mean (8 authors)	**$c = 1.01708 - 0.00416 * FC$**	**(R2= 0.9949)**

Coefficient "c" by other methodologies

10 Australia coeff. 5	$c = 0.95125 - 0.00067 * FC$	(R2= 0.9987)
11 Louisiana coeff. 1.3	$c = 1.00773 - 0.00406 * FC$	(R2= 0.9993)
12 South Africa BFW 25%	$c = 1.00645 - 0.00338 * FC$	(R2= 0.9994)

Obs.:
- Australia: pol coefficient 5 and the analysis is of the first expressed juice, not using the press method.
- Louisiana: The "brix-free water" is fixed as 30% fiber % cane, using the core sampler/press method.
- South Africa: The "brix-free water" is fixed as 25% fiber % cane, using a prepared cane sample, and the wet disintegrator method.

The value of "c" will always be less than 1, as the pol % extract juice is always greater than the pol % absolute juice. The "c" value is always closer to unity for the cane of lower fiber content, as the multiplier "b" in the linear regression equations is always negative.

The coefficient "c" results would vary according to the pressure used, the amount of pressed cane, the time of pressing, and the homogeneity of the cane sample preparation (**Figure 8.6**).

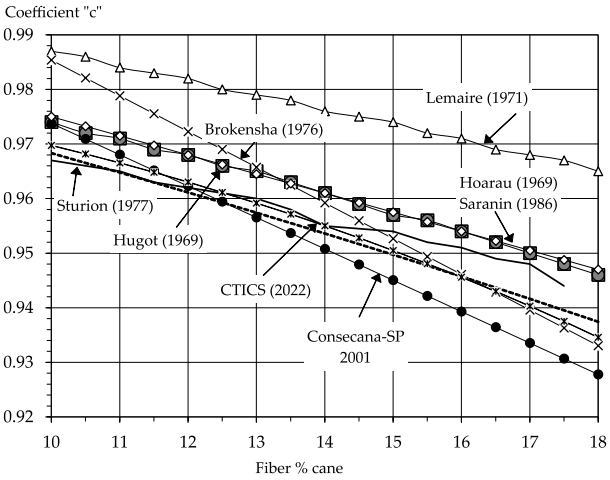

Figure 8.6 – Coefficient "c" obtained by eleven authors under different condi-tions of gross cane or clean cane, sample preparation and sub-sample, pressure and time of pressure, and type of press.

The pol % cane is obtained as a function of the pol % extracted juice multiplied by the percentage of absolute juice in the cane (100 - Fiber % cane) and by the coefficient "c".

The Consecana-SP coefficient "c" (1.0313 - 0.00575 ∗ Fiber % cane) evaluates the transformation of the pol % extracted juice into pol % absolute juice for the working conditions of the Brazil core/press system. This equation was determined in research (not published) carried out

at the beginning of the implementation of the cane payment system in Brazil (1980s). **Table 8.6** shows the coefficients "c" values for three fixed values of fiber % cane.

Table 8.6 – Coefficients "c" obtained by several authors and methodology and fixing three levels of fiber % cane (Authors 1 through 8 by core/press and 9 through 11 by other methods).

Author	**12.0**	**14.0**	**16.0**	**Country**
1 Hoarau (1969)	0.9675	0.9606	0.9536	Mauritius
2 Lemaire (1971)	0.9816	0.9762	0.9707	Guadaloupe
3 Hugot (1974)	0.9610	0.9533	0.9456	Reunion
4 Brokensha (1976)	0.9723	0.9592	0.9462	South Africa
5 Sturion (1977)	0.9620	0.9562	0.9504	Brazil
6 Saranin (1986b)	0.9680	0.9610	0.9540	Australia
7 Consecana (2001)	0.9623	0.9508	0.9393	Brazil
8 CTICS (2022)	0.9627	0.9539	0.9452	Reunion
Mean (8 authors)	**0.9672**	**0.9588**	**0.9505**	
9 Australia coeff. 5	0.9432	0.9419	0.9405	Australia
10 Louisiana coeff. 1.3	0.9590	0.9509	0.9428	USA
11 South Africa BFW	0.9659	0.9591	0.9524	South Africa

Upon initial review, it may appear that the outcome of "pol % cane" will differ depending on the author. However, the lower the pressure, the greater the pol % juice and the lower the coefficient "c", that is, the same pol % juice cannot be applied to the different equations of the coefficient "c".

For the most common range of fiber % cane, between 12% and 16%, the results obtained by the authors, except for Lemaire (1971), would estimate the pol % cane value to be within 0.1 unit (**Table 8.7**).

Table 8.7 – Pol % cane supposing that the pol % juice is the same (16.5) for the different equations of the coefficient "c" and fixing three levels of fiber % cane (Authors 1 through 8 by core/press and 9 through 11 by other methods).

Author	**12.0**	**14.0**	**16.0**
1 Hoarau (1969)	14.1	13.6	13.2
2 Lemaire (1971)*	14.3	13.9	13.5
3 Hugot (1974)	14.0	13.5	13.1
4 Brokensha (1976)	14.1	13.6	13.1
5 Sturion (1977)	14.0	13.6	13.2
6 Saranin (1986b)	14.1	13.6	13.2
7 Consecana (2001)	14.0	13.5	13.0
8 CTICS (2022)	14.0	13.5	13.1
Mean (8 authors)	**14.0**	**13.6**	**13.2**
9 Australia coeff. 5	13.7	13.4	13.0
10 Louisiana coeff. 1.3	13.9	13.5	13.1
11 South Africa BFW	14.0	13.6	13.2

It is noted that "Australia coeff. 5" underestimates the pol % cane by 0.2 to 0.3 units using the first expressed juice as it was the same as the extracted juice from the press. For the Louisiana core/press system, where it was assumed that the brix-free water is 30% of the fiber % cane (Rein, 2017), the underestimation is only 0.1 units.

In South Africa, where the "brix free water" is taken as 25%, the results of pol % cane match those of the average of eight authors. This suggests that the assumption of 25% brix-free water is appropriate, but more investigations are needed on this aspect.

Coefficient "c1" for the estimation of brix % cane

Only a few authors (Brokensha *et al*, 1976; Sturion and Fernandes, 1979; Saranin, 1986) have researched the "c1" coefficient. Their results have been inconclusive. The "c1" coefficient has been disregarded in Brazil since brix % cane is not used in the core/press system for cane payment, agronomic management, and factory control.

It is therefore recommended that, as long as no good alternative is presented for calculating the "c1" coefficient, that c1 be assumed to be unity and that the following equation for brix % cane should be used.

$$\text{Brix \% cane} = \text{Brix \% juice} * (1 - 0.01 * \text{Fiber \% cane})$$

9 Formulas for recoverable sugar

Since the later decades of the 19th century, researchers have been attempting to develop a formula to estimate the quantity of sugar that can be produced from sugarcane, taking into account the quality of the cane feedstock and various indicators of sugar factory process performance.

All formulas proposed use analytical data of pol, brix, purity, and fiber % cane and consider sugar losses in cane milling bagasse, juice clarification muds, boiling house molasses, and undetermined losses. However, the sugar manufacturing process is complex and its mass balance presents difficulties.

The theoretical recoverable sugar yield estimates can be used for planning the production of sugar under different scenarios; for calculating the price of cane for cane payment; for the simulation of yields from alternative investments; and for calculating the relative industrial efficiency (Wright et al., 2007).

Important: The formulas proposed or discussed in this chapter apply only to factories producing sugar and final molasses. For those plants producing sugar and ethanol from juices and intermediate syrups, such as Brazilian sugar mills, the estimation of yields is described in Chapter 10 "Theoretical yields of sugar, ethanol, and molasses".

9.1 Sugar losses in the factory

Sugar losses in the factory can be classified into two groups: "determined" and "undetermined" (**Figure 9.1**).

During the sugar production process, there are several points in the process where sucrose is lost. However, only three of these losses are effectively measured: final bagasse, filter cake, and final molasses.

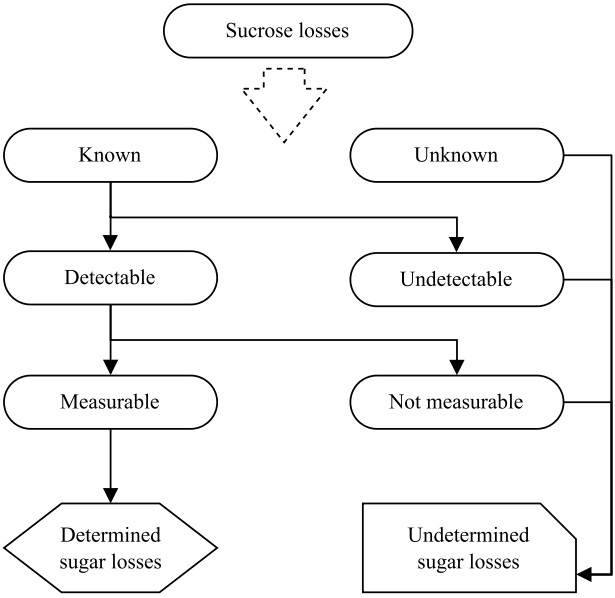

Figure 9.1 – Sugar loss classification diagram.

Sugar and ethanol production can result in several **types of losses** - physical, chemical, microbiological, and economic. Physical losses occur in final bagasse, filter cake, wastewater, juice, and high sugar concentration syrup leaks. Chemical losses occur due to sucrose hydrolysis (inversion) and chemical and thermal destruction of sugars. Microbiological losses happen due to microorganisms like bacteria and yeast. Economic losses occur when low-quality products require reprocessing after customer returns. A schematic indicating some of these losses is shown in **Figure 9.2**.

While the sugars lost in wastewater are measured in Brazilian sugar mills, this result is not very precise due to the difficulty of measuring water volume and evaluating its sugar content. Any other sugar losses that are not included in the calculations will be categorized as "undetermined losses".

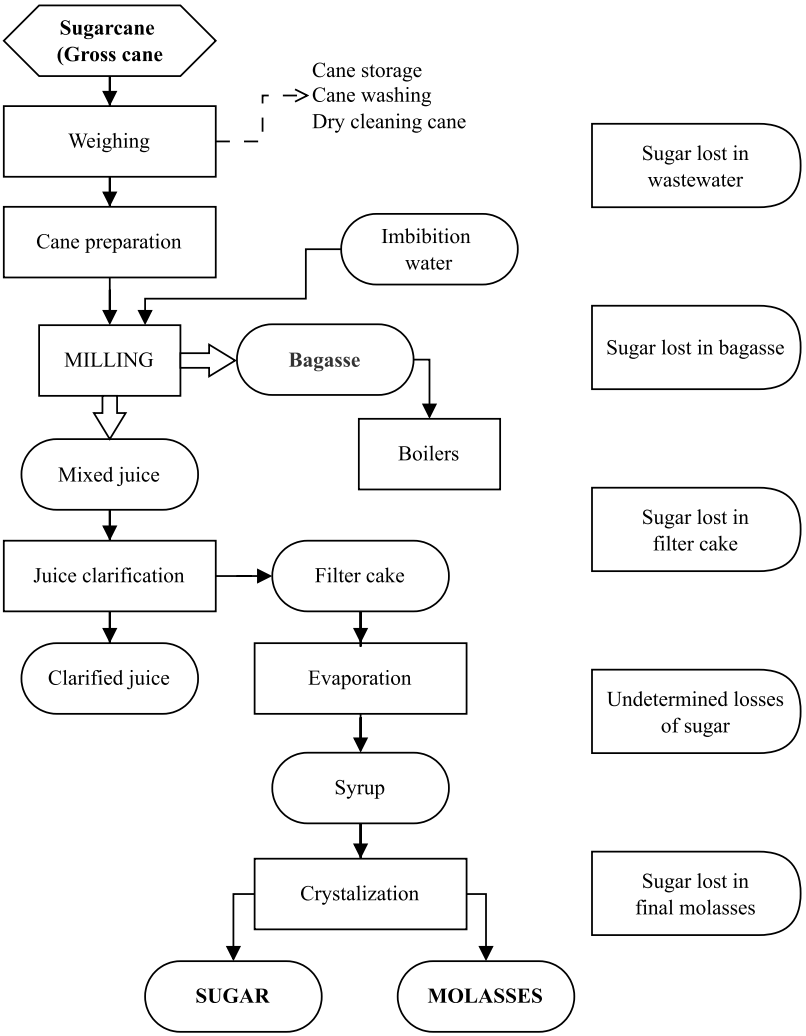

Figure 9.2 – Simplified diagram of sugar production with main losses of sugar.

The balance of sucrose lost in the process of sugar production (in kilogram) from cane can be presented for each designated period of operation as:

Total sucrose (or pol) in processed cane = Total processed cane (t) * Sucrose (or Pol) % cane / 100

Obs: When the sucrose % cane value is not available, it is acceptable to use the pol % cane result.

Total sucrose in sugar produced = Sugar produced (t) * Pol % sugar

Obs: Pol % sugar calculated for each period for each type of sugar.

Total sucrose lost = Total sucrose or pol in milled cane - Total sucrose in produced sugar.

Determined losses = Sum of sugar lost in final bagasse, filter cake, and final molasses.

Undetermined losses = Total sucrose lost - Determined losses.

Overall Recovery = 100 * Total sucrose in produced sugar / Total sucrose or pol in processed cane.

9.2 SJM boiling house recovery formula by Noël Deerr

The performance of the sugar manufacturing sector can be measured by "Boiling House Recovery" (BHR), which is the percentage ratio between the pol recovered in the product sugar and the pol in the mixed juice. The BHR considers the losses in the clarification process of the mixed juice (filter cake) and, the losses of sugar in the molasses.

The SJM efficiency, also called "SJM recovery", indicates the percentage of sucrose that should be crystallized in the boiling section depending on the true purity of the sugar (S), the apparent purity of the mixed juice (J), and the true purity of the molasses (M). It is acceptable to use

the apparent purity (100 ∗ pol/brix) for the sugar and the mixed juice. However, for the final molasses the difference between pol and sucrose is too large, and the true sucrose purity for M in the formula should be used.

The deduction of the SJM formula, as presented below, is based on the original work of Noël Deerr (1911).

Assume that "*j*" is the concentration of sucrose per unit of dry matter (true purity), with "*c*" being the amount of sugar removed and "*d*" representing the non-sugars present in the material. The unit sucrose content is represented by "*s*", which is contained in $(c + d)$. The residue (molasses) will be equal to $(1 - c - d)$, which contains "*m*" of sucrose per unit of dry matter. Thus:

$$j = (c + d) * s + (1 - c - d) * m$$

This equation can be modified to:

$$(c + d) = \frac{j - m}{s - m}$$

Multiplying both sides of the previous equation by s/j:

$$s * \frac{(c + d)}{j} = \frac{s * (j - m)}{j * (s - m)}$$

The result of "$s * (c + d)$" is the amount of sucrose in the final product (sugar) and *j* is the amount of sucrose in the original material (mixed juice), which makes the left component of the previous equation $[s * (c + d)/j]$ as the result of the percentage of sucrose recovered in the sugar percent of the original material, resulting in the Deerr SJM formula:

$$SJM = 100 * \frac{s * (j - m)}{j * (s - m)}$$

Assuming that the recovery is of pure sucrose (sugar purity of 100%) and the juice is really a syrup, the estimated Boiling House Recovery (BHR) would be given by the SJM recovery formula:

BHR = SJM Recovery = 100 * 100 * (Syrup purity - Molasses purity) / (Syrup purity * (100 - Molasses purity))

Example: Supposing syrup's apparent purity is 84.91% and molasses true purity is 38.06%, the SJM Recovery for sugar of 100% purity will be:

SJM Recovery = 100 * 100 * (84.91 - 38.06) / (84.91 * (100 - 38.06)) = 89.08%

For the same syrup and producing B-molasses with apparent purity of 48.72% the SJM recovery will be 83.12%. In the case of the Brazilian sugar ethanol mills, the B-molasses may be mixed with juice and used for ethanol production.

9.3 Winter formula for boiling house recovery

According to Legendre and Henderson (1972), in 1897 Winter observed the actual mill performance of several factories in Java and concluded that for each point of "impurity" or apparent nonsucrose in the mixed juice (brix – pol), there was 0.4 point of sugar lost in molasses (called "**retention**"), and including juice treatment (filter cake) and part of the total undetermined losses, e.g, in the "boiling house".

The "Recovered Sugar by Winter" (RSW):

RSW = Pol % juice - 0.4 * (Brix % juice - Pol % juice)
= 1.4 * Pol % juice - 0.4 * Brix % juice

Since the Brix % juice = 100 * Pol % juice / Purity of juice:

RSW = 1.4 ∗ Pol % juice - 0.4 ∗ 100 ∗ Pol % juice / Purity of juice

RSW = Pol % juice ∗ (1.4 - 40 / Purity of juice)

Thus the BHR by Winter = 100 ∗ (1.4 - 40 / Purity of juice)

Example: Supposing pol % mixed juice equals 10.95% and the juice's true purity is 86.08%.

Recovered sugar % juice Winter = 10.95 ∗ (1.4 - 40 / 86.08) = 10.20% juice

BHR by Winter = 100 ∗ (1.4 - 40 / 86.08) = 93.53%

Because it is straightforward, the well-known "Winter Formula" was introduced in several sugar cane-producing countries, and used for factory control and cane payment based on cane quality.

Winter formula related to the SJM formula

Deerr (1911) states that: "Formulas of similar form and obtained by different reasoning have been proposed by **Winter**, Geerligs, Rose, Carp, Lohman, and Hazewinkel in Java, between the years 1894 and 1903. Geerligs gives a complete discussion of these in the Dutch edition of "Cane Sugar and its Manufacture."

Considering the molasses true purity as 28.57%, and sugar purity equal to 100%, the Winter recovery formula can be deduced from SJM.

SJM Recovery = 100 ∗ 100 ∗ (Juice purity - Molasses purity) / (Juice purit ∗ (100 - Molasses purity))
= 100 ∗ 100 ∗ (Juice purity - **28.57**) / (Juice purity ∗ (100 - **28.57**))
= 100 ∗ 100 ∗ (Juice purity - 28.57) / (Juice purity ∗ 71.43)
= 100 ∗ 100 ∗ (Juice purity/ (Juice purity ∗ 71.43) - 28.57 / (Juice purity ∗ 71.43))
= 100 ∗ 100 ∗ (1 / 71.43 - 28.57 / 71.43 ∗ Juice purity)

Winter recovery formula = 100 * (1.4 - 0 40 / Juice purity)

Note that an A- molasses true purity level of 28.57% is a hypothetical situation, and such a low final molasses true purity level cannot be achieved under normal circumstances.

Because there is a large and significant variation in final molasses purity levels between sugar mills, and within the same mill during a harvest, the **application of the SJM formula should be generally preferred over the Winter formula**. The SJM formula allows the calculation of estimated BHR with any true purity of molasses and purity of mixed juice or syrup, for a sugar purity of 100% or other.

Generic Winter formula

Estimating BHR by Winter with a fixed value for molasses' true purity (28.57%) is easy to understand.

BHR Winter = 100 * (1.4 - 0.40 / Molasses purity)

Generically, a "Theoretical BHR" can be expressed by taking the Winter value 1.4 as a variable "Factor W1" and Winter value 0.40 as a variable "Factor W2":

Theoretical BHR = 100 * (W1 - W2 / Molasses purity)

By using the SJM equation the factors W1 and W2 can be evaluated as simple functions of molasses purity (M):

Theoretical BHR = 100 * (W1 - W2 / Molasses purity)

Where:

Factor W1 = 1 / (1 - Molasses purity / 100)
Factor W2 = 1 / (1 / Molasses purity - 0.01)
Molasses purity (M) = Factor W2 / Factor W1

9.4 Examples of recoverable formulas

From the turn of the 19th century to the 20th century, several methods and formulas were suggested to estimate BHR based on cane analytical quality, such as the well-known SJM and Winter formulas.

To exemplify the probable sugar results in the same unit, that is, sugar 100% and kg/t cane, the results of the arithmetic mean of 14 sugar factories in South Africa in the harvests from 2001 to 2017 were used (**Table 9.1**). These data were collected on the SASTA website[1].

Table 9.1 – Results of 17 harvest seasons (2001-2017) in 14 South African sugar mills.

Sucrose % cane	13.55%
Fibre % cane	15.04%
Brix % cane	15.98%
Syrup apparent purity	84.91%
Pol % bagasse	1.10%
Moisture % bagasse	50.30%
Fibre % bagasse	4767%
Boiling House Recovery obtained (sucrose)	87.10%
Molasses true purity	38.06%

Cane true purity (calculated) = 100 * Sucrose % cane / Brix % cane
= 100 * 13.55 / 15.98 = 84.79%

Examples:	**1**	**2**	**3**
Molasses purity	28.57	33.33	55.00
Factor W1 = 1/ (1 -Molasses purity/ 100)	1.40	1.50	2.22
Factor W2 = 1/ (1 / Molasses purity - 0.01)	40.0	50.0	122.2
Molasses purity = Factor W2/ Factor W1	28.57	33.33	55.00

[1] *https://sasta.co.za/congress-proceedings/*

1 = original Winter coefficients, 2 = Australia CCS, and 3 = common value for Brazil (massecuite B as final molasses).

Definitions

The variable with "true purity" always refers to the relation "sucrose/refractometer brix" for the data from South African mills.

CCS: Commercial Cane Sugar (Australia)
ERC: Estimated Recoverable Crystal (South Africa)
TRS: Theoretical Recoverable Sugar (Louisiana/USA)
BHR: Boiling House Recovery, the relation between total sucrose in produced sugar with the total sucrose in the mixed juice.
BHE: Boiling House Efficiency, the relation between obtained BHR and theoretical BHR by SJM with sugar 100% (S), cane true purity (J), and molasses true purity (M) from CCS or ERC or TRS.

9.4.1 Australia CCS

In Australia in 1888, Dr. Kottman proposed the Commercial Cane Sugar (CCS) formula. This is a measure of pure sucrose recoverable from the cane and has been used since 1915 to determine the cane payment for quality (Mackintosh, 2000).

The CCS formula is similar to the Winter formula, with a different assumed value of the "**coefficient of retention**". While Winter estimates the recovery from mixed juice with a retention of 0.4 per unit of juice impurity (Brix - pol), CCS estimates the percentage recovery from cane with a retention of 0.5. The SJM formula can replace both equations.

$$\text{CCS} = \text{Pol \% cane} - 0.5 * (\text{Brix \% cane} - \text{Pol \% cane})$$

$$\text{CCS} = 1.5 * \text{Pol \% cane} - 0.5 * \text{Brix \% cane}$$

$$\text{CCS} = 10 * \text{Pol \% cane} * (1.5 - 50 / \text{Cane true purity})$$

Wright (2005) presented a useful adaptation of the CCS formula, nominated RCS:

RCS = 0.945 * 100 / Pol % sugar * 10 * Pol % cane * (1.5 - 50 / Cane true purity)

Example of Australia CCS calculation

From **Table 9.1**, with Brix and pol % cane, it is possible to calculate:

CCS = Pol % cane - 0.5 * (Brix % cane - Pol % cane)
= 13.55 - 0.5 * (15.98 - 13.55) = 12.335%

Equivalent to 123.35 kg/t cane

Calculating RCS formula by Wright (2005):

RCS = 0.945 * 100/ Pol % sugar * 10 * CCS
= 0.945 * 100 / 100 * 10 * 12.335 = 116.57 kg/t cane

9.4.2 Louisiana formula for sugar recovery, the TRS

In Louisiana, the cane is sampled using an oblique core sampler. The cane sample is disintegrated and the juice is extracted using a hydraulic press (core/press system). The brix, pol, and fiber results are used to calculate the "Theoretical Recoverable Sugar" (TRS). This has been used for cane payment systems based on quality for several years.

The TRS formula assumes a lost absolute juice % cane figure of 56.67 and uses the Winter-Carp formula with a Boiling House Recovery of 96% to predict the sugar recovery (Rein, 2007). An explanation for the use of the coefficient 56.67 has not yet been found.

The original TRS formula with a BHR of 96% with the TRS given in Lbs/ton units is:

TRS = (100 - 56.67 * Fiber % cane / (100 - Fiber % cane)) * (0.28 * Pol % cane - 0.08 * Brix % cane)

The first part of the last equation represents the "Extraction" and other sugar losses. The second part is called "Retention" (Birkett & Stein, 2007) or boiling house recovery (BHR) by Winter. Multiplying by 0.96 converts a TRS 96% value into a TRS 100% result:

TRS 100% = TRS 96% * 0.96

Converting the BHR element of the TRS equation into the Winter type formula:

TRS 96% (Lbs/ton cane units) = (100 - 56.67 * Fiber % cane / (100 - Fiber % cane)) * (1.4 - 40 / Cane apparent purity) * 2

Regarding the part of the formula for the extraction, if the fiber % cane is 12.5%, the extraction result is 91.9%, and if the fiber % cane is 15%, then the extraction is predicted by the TRS 96% formula to be 90.02%. These extraction values (pol extracted % total pol in cane) are much lower than the current technology standard for milling of around 97% (ranging from 96% to 98%). The losses for filter mud and undetermined loss must have been deducted from the milling extraction.

Example of Louisiana TRS

From **Table 9.1**, TRS is calculated in Lbs/ton units:

TRS 96% = (100 - 56.67 * Fiber % cane / (100 - Fiber % cane)) * (0.28 * Sucrose % cane - 0.08 * Brix % cane)
= (100 - 56.67 * 15.04 / (100 - 15.04)) * (0.28 * 13.55 - 0.08 * 15.98)
= 226.324 Lbs/t cane

To express in kg of sugar 100%/t of cane, the original TRS formula must be divided by 2 to get kg/t units and multiplied by 0.96 to convert to TRS 100%.

TRS 100% = (100 - 56.67 * Fiber % cane / (100 - Fiber % cane)) * (0.28 * Sucrose % cane - 0.08 * Brix % cane) * 0.96/ 2
= (100 - 56.67 * 15.04 / (100 - 15.04)) * (0.28 * 13.55 - 0.08 * 15.98) * 0.96 / 20 = 108.64 kg/t cane

Extraction TRS = (100 - 56.67 * Fiber % cane / (100 - Fiber % cane))
= (100 - 56.67 * 15.04 / (100 - 15.04)) = 89.97%

Naturally, the extraction of pol % pol in cane appears to be very low in this example (89.97%), as other sugar losses (mud loss, undetermined loss) are part of it. Using the Winter format for the BHR element of the TRS:

TRS 100 % cane = Extraction / 100 * Sucrose % cane * (1.4 - 40 / Cane apparent purity) * 0.96
= 89.97 / 100 * 13.55 * (1.4 - 40 / 84.79) * 0.96 = 10.864%

Thus, the expected apparent purity of the molasses by TRS is the same as in Winter.

Molasses apparent purity by TRS = 100 * 0.08 / 0.28 = 28.57%

Theoretical Boiling House Recovery (BHRt):

BHR by TRS = 100 * 100 * (Cane true purity - Molasses TRS purity) / (Cane true purity * (100 - Molasses TRS purity))
= 100 * 100 * (84.79 - 28.57) / (84.79 * (100 - 28.57)) = 92.83%

Boiling House Efficiency (BHE):

BHE by TRS = 100 * Obtained BHR / Theoretical BHR by TRS
= 100 * 87.10 / 92.83 = 93.83%

See Obtained BHR in **Table 9.1**.

9.4.3 South Africa Estimated Recoverable Crystal

The sugar yield estimate from cane in South African mills uses the ERC or "Estimated Recoverable Crystal", a formula Van Hengel developed in 1974.

ERC = a ∗ Pol % cane - b ∗ Non pol % cane - c ∗ Fiber % cane

The coefficients "a", "b" and "c" represent the sucrose or pol losses:

a = undetermined loss and the filter cake loss per unit of pol in cane,
b = the final molasses loss in the sugar boiling house per unit of non-sucrose (impurities) in cane,
c = the bagasse loss per unit of fiber in cane.

The values of the multipliers in the ERC equation can be obtained by regression of the recorded pol recovery against the recorded pol, non-pol, and fiber % cane values for weekly periods. The recovery formula had the following constants for the year under review by van Hengel (1974):

ERC = 0.9799 ∗ Pol % cane - 0.4646 ∗ (Pol % cane - Brix % cane) - 0.0483 ∗ Fiber % cane

ERC coefficients are calculated at the end of each milling season by equating the weighted mean with the actual value. Rein (2002) provided coefficients a, b, and c as 0.98, 0.5, and 0.02 respectively. It was noted that the extraction levels in SA had improved greatly since Hengel (1974) calibration, and the value of the coefficient c had reduced. Therefore:

ERC = 0.98 ∗ Pol % cane - 0.5 ∗ (Brix % cane - Pol % cane) - 0.02 ∗ Fiber % cane

Or, to have a similar nomenclature to the Australian CCS formula, albeit with the addition of an extra term for losses associated with the fiber content:

$$ERC = 1.48 * Pol\ \%\ cane - 0.5 * Brix\ \%\ cane - 0.02 * Fiber\ \%\ cane$$

Example of South Africa ERC

From **Table 9.1** it is calculated:

$$ERC = 0.98 * Pol\ \%\ cane - 0.5 * Non\text{-}pol\ \%\ cane - 0.02 * Fibre\ \%\ cane$$
$$= 0.98 * 13.55 - 0.5 * (115.98 - 13.55) - 0.02 * 15.04 = 11.763\% =$$
$$117.63\ kg/t\ cane$$

9.5 Generic formula for recoverable sugar

The SJM and Winter formulas only consider sucrose lost in molasses. Therefore, they cannot be used to predict sugar yield without considering other losses: final bagasse, filter cake, and undetermined losses.

9.5.1 Criteria for sugar yield formula

The formula for estimating sugar yield will be used for cane payment by quality, and for this reason, must be simple and easily understandable to be accepted by all involved.

The coefficients (fixed values) must be representative of the reality of the regions where they will be applied.

The input data must be the pol and brix of the juice extracted in the press in the core/press system (Brazil, Louisiana, Reunion), the pol and brix of the first expressed juice (Australian system), or the pol and brix of the cane by the wet disintegrator system (South African), and the fiber % cane. These are analyzed data when the cane is delivered for processing.

Losses of sucrose in the process must be deducted from the sucrose (pol) delivered with the cane. There are four major sugar loss areas,

that is, in the final bagasse from the mill or diffuser (between 2.5% and 3.5%), in the filter cake (around 0.2 to 1.0%), in the final molasses produced, and in undetermined losses (normally between 0.5% and 3.0%, including sugar lost in wastewater).

The excellent performance of South African sugar mills, as well as the high quality of available and detailed benchmarking results, can be used as a reference (**Table 9.2** and **Table 9.3**). The coefficients must be adapted for a specific region or country.

Table 9.2 – Losses of sucrose % sucrose in cane in 14 South African sugar mills in 17 harvest seasons (arithmetic means for 2001 to 2017).

Description	Bagasse	Filter Cake	Molasses	Undetermined	Total lost
Mean	2.52	0.21	10.00	2.36	15.09
Max. value	3.25	0.37	11.84	3.58	19.04
Min. value	1.97	0.14	8.62	1.76	12.71
Amplitude	1.28	0.23	3.22	1.82	6.33
Std. Deviation	0.40	0.07	0.83	0.50	1.68
Conf. Int. 95%	0.21	0.04	0.43	0.26	0.86
Participation %	16.7	1.4	66.3	15.6	100

The "Total lost" on the first line (Mean) of **Table 9.2** indicates that 15.09% was not recovered in the industrial process, with 10% units of this loss being in the final molasses. The means of total recovery (sucrose in the sugar produced % sucrose in the milled cane) in the period was 84.91%.

The mean values for the overall recovery, the combined losses in bagasse, filter cake, and undetermined (BCU), the molasses loss, the fiber % cane, and the mills/diffuser extraction are shown in **Table 9.3**, along with their statistics. The excellent extraction value is due to the use of cane diffusers and high technology in milling.

Table 9.3 – Arithmetic means of Overall Recovery (O.R.), losses of sucrose in Bagasse, filter Cake, and Undetermined (BCU), and the final molasses loss, all for 17 harvest seasons (from 2001 to 2017) in 14 South African sugar mills.

Description	Overall Recovery	BCU Loss	Fiber % cane	Extraction sucrose	Total lost
Mean	84.91	5.09	10.00	15.0	97.5
Max. value	87.29	7.2	11.84	15.9	98.0
Min. value	80.96	3.89	8.62	14.7	96.8
Amplitude	80.96	3.31	3.22	1.3	1.3
Std. Deviation	1.68	0.93	0.83	0.32	0.4
Conf. Int. 95%	0.86	0.48	0.43	0.16	0.21

9.5.2 Predicted Sugar Yield (PSY)

After a lengthy consideration of sugar recovery formulas from various countries, this author proposes a formula, tentatively named"Predicted Sugar Yield" (PSY) to estimate the pure sugar yield in units kg/t cane. The formula presented is:

$$\mathbf{PSY = 10 * Pol\ \%\ cane * BCU\% * BHRt\% / 100}$$

Where the terms BCU% and BHRt are defined in the following sections.

Sugar lost in final bagasse, filter cake, and undetermined

Fiber % in cane varies greatly based on sample type, methodology, and non-stalk (trash) influence. So, despite fiber's considerable impact on extraction, correlating it with the extraction process is not feasible for all plants, regions, and harvest periods.

The extraction of sucrose or pol % sucrose or pol in the cane is very stable in all sugar mills with adequate control. Usually, the extraction re-

mains between 96.5 and 97.5 for a tandem of six mills or a diffuser/mill system. Extraction is usually lower for milling tandems of less than six mills or using inadequate technology.

The sugar lost in filter cake represents less than 0.5% of total losses. The arithmetic mean in South African mills (2001-2017), mostly with diffuser systems and hand-cut burned cane, was 0.21 $\pm$0.04%. Factories with milling trains would generally have higher filter cake losses.

Undetermined losses of sugar % total sucrose in cane, from the same source and period, was 2.36 $\pm$0.26%. Australian mills often record lower undetermined losses.

Sugar lost in final molasses is directly related to the cane or juice purity (**Figure 9.3**).

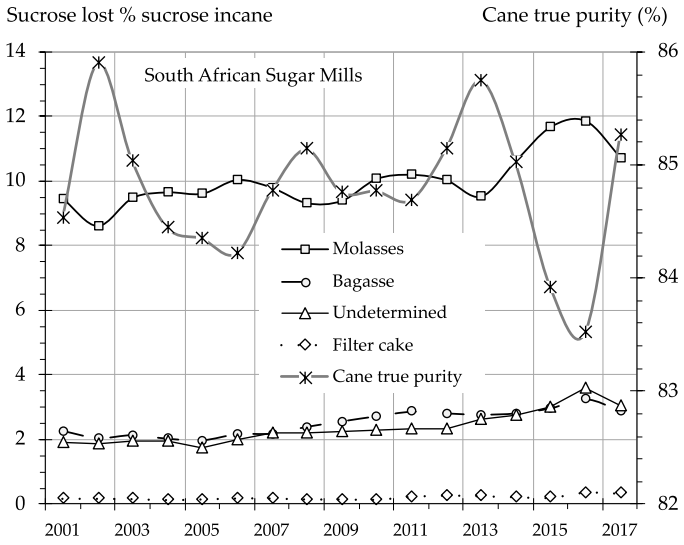

Figure 9.3 – Sucrose lost % sucrose in cane and cane true purity from 2001 to 2017 in 14 South African sugar mills.

The lowest loss of sucrose in molasses occurred in 2002 (average of 8.62%) when the cane's true purity was an exceptional 85.9%. In 2016, when the sugarcane purity was 2.4 percentage points lower at 83.5% the molasses loss was 11.84%, an increase of 37.4% over the 2002 value.

The good growing and harvesting conditions in Australian mills result in higher cane purity values, and consequently lower molasses losses, though the consequent low RS content of the impurities does make it harder to achieve good exhaustion of the final molasses.

For the losses of sucrose in **B**agasse, filter **C**ake, and **U**ndetermined (BCU) considering only the results presented by South Africa, the coefficient BCU% can be adopted as **0.9540**. This value assumed that these combined losses are 4.60% of the pol in cane.

Sugar lost in final molasses (BHRt%)

We can use the SJM formula to calculate the theoretical boiling house recovery (BHRt). It depends on the true purity of the sugar (S) (fixed as 100%), the apparent purity of the juice (J), and the true purity of the molasses (M).

SJM = 100 * (Juice purity - Molasses true purity) / (Juice purity * (100 - Molasses true purity))

As discussed in Section 9.3 about the Winter formula, the "Theoretical BHR" can be expressed as:

Theoretical BHR = 100 * (W1 - W2/ Juice purity)

Where the coefficients W1 and W2 can be obtained from SJM:

Factor W1 = 1 / (1 - Molasses purity / 100)
Factor W2 = 1 / (1 / Molasses purity - 0.01)

Assuming molasses true purity of 38.00%, instead of 28.57% from the Winter formula, the estimated BHR is:

Factor W1 = 1 / (1 - 38.00 / 100) = 1.6129
Factor W2 = 1 / (1/ Molasses purity - 0.01) = 61.29
Theoretical BHR = 100 ∗ (1.6129 - 61.29 / Juice apparent purity)

Replacing BCU (0.9540) and BHRt in the PSY formula we then obtain, for SA conditions:

PSY = 1000 ∗ Sucrose % cane ∗ 0.9540 ∗ (1.6129 - 61.29 / Cane true purity)

It is possible to replace "Sucrose % cane" with "Pol % cane". In countries other than South Africa, "Cane true purity" can be approximated with "Extract juice purity from the core/press method" in Brazil, Louisiana, and Reunion, while the first expressed juice purity could be used in Australia. However, in these cases, an adjustment to the BCU coefficient of the PSY formula would be required.

Regarding molasses' true purity, it is important to note that the apparent purity of molasses (100 ∗ Pol % molasses/ Brix % molasses) differs significantly from its true purity (100 ∗ sucrose % molasses / Soluble solids % molasses), as shown in **Figure 9.4** for South Africa, where the average difference is around 2.5 percentage units. The difference is greater in Australia where the maturity of the crop is high and the ratio of RS to Ash in the final molasses is low. When using the molasses apparent purity, an adjustment to the BCU coefficient will certainly be necessary.

9.5.3 Comparing theoretical formulas sugar yield

Based on the four formulas for estimating the theoretical sugar yield reviewed here, it can be concluded that the PSY is very close to the actual sugar yield obtained in South African sugar mills since this formula was developed based on and calibrated to South African results.

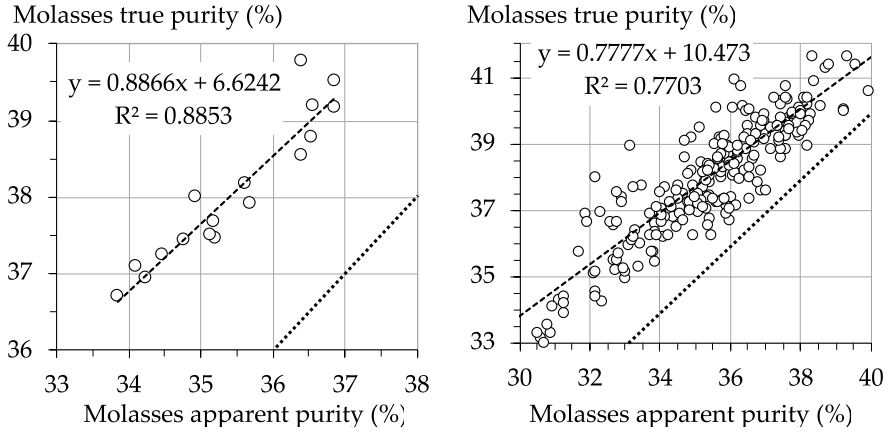
Molasses true purity (%)
y = 0.8866x + 6.6242
R² = 0.8853
Molasses apparent purity (%)
Molasses true purity (%)
y = 0.7777x + 10.473
R² = 0.7703
Molasses apparent purity (%)

Figure 9.4 – Mean of molasses purity in the period of 17 harvest seasons (left) at 14 South African sugar mills (right). Molasses true purity is as sucrose % refractometer brix.

However, this is not the case with CCS and ERC, as they indicate higher values, while TRS indicates lower values of the expected sugar yield in South African diffusers/mills (**Figure 9.5** and **Figure 9.6**).

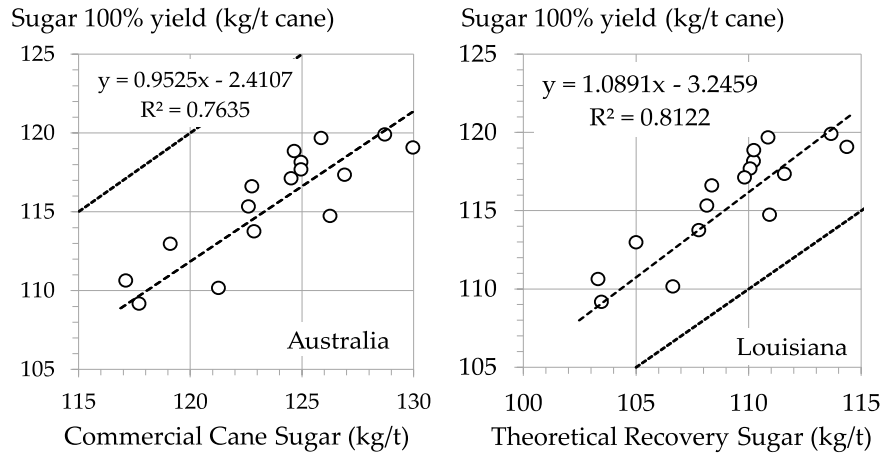

Figure 9.5 – CCS and TRS versus sugar yield.

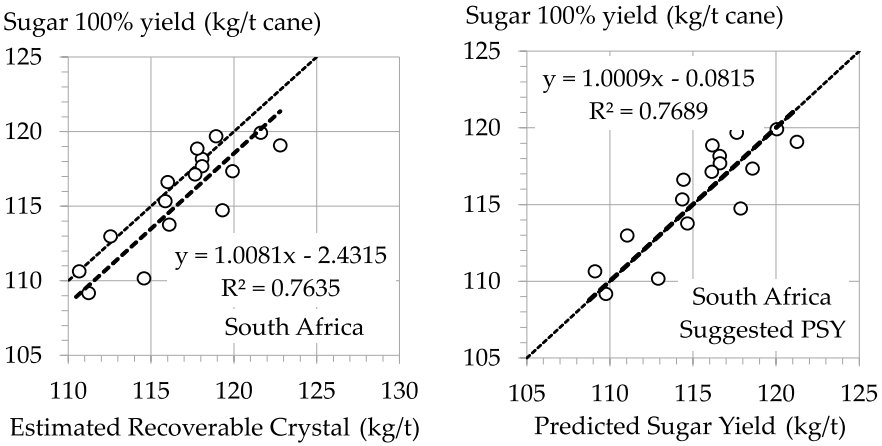

Figure 9.6 – ERC and PSY versus sugar yield.

The CCS formula in Australia and the TRS in Louisiana, USA, were developed for cane payment systems and, as a result, differ from the others. If the goal is to estimate sugar production for a specific situation, it would be reasonable to choose the suggested PSY, while adjusting BCU losses and molasses true purity.

The sugar yields predicted by the five formulae using their locally calibrated coefficients are shown in **Table 9.4**.

Table 9.4 – Theoretical yield of sugar 100% (kg/t cane) using the average mean of 17 harvest seasons (2001-2017) in 14 South African sugar mills.

Symbols	Sugar yield	Correction coefficient	Overall Recovery %
OSY	115.1 ±2.2	1.0000	84.93
CCS	123.4 ±2.0	0.9330	91.03
RCS	115.2 ±1.9	0.9993	84.99
TRS	108.6 ±1.8	1.0593	80.18
ERC	116.6 ±1.9	0.9872	86.03
PSY	115.1 ±1.9	1.0002	84.92

OSY: Obtained Sugar Yield, CCS: Commercial Cane Sugar, RCS: Recovery Cane Sugar, TRS: Theoretical Recovery Sugar, ERC: Estimated Recoverable Crystal, PSY: Predicted Sugar Yield

The three formulae (CCS, TRS, and ERC) can give the same result as PSY, and the true sugar yield only if their coefficients are recalibrated to the same local conditions. The CCS formula in Australia and the TRS in Louisiana, USA, were developed for **cane payment systems** and, as a result, differ from the others. If the goal is to estimate sugar production for a specific situation, it would be reasonable to choose the suggested PSY, while adjusting BCU losses and molasses true purity.

The results of 17 harvest seasons (2001 to 2017) in the 14 South African sugar mills show that RCS (Australia, Wright 2005), ERC (South Africa), and PSY (proposed flexible formula) oscillated around the true yield of sugar (kg/t of cane) obtained by the mentioned source (**Figure 9.7**). If the "correction coefficient" is applied (see **Table 9.4**), any of the five equations can be used to predict theoretical sugar recovery.

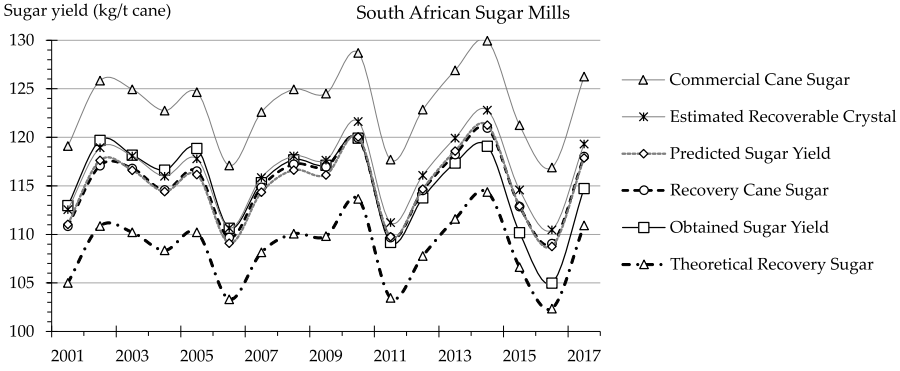

Figure 9.7 – Obtained sugar yield and theoretical estimative with five formulas during 17 harvest seasons (2001-2017) in 14 South African sugar mills.

10 Theoretical yields of sugar, ethanol, and molasses

Different formulas to estimate the amount of sugar that can be recovered, considering the quality of the cane and the characteristics of the sugar mill, have been proposed and are in use in several countries Legendre & Henderson (1972). However, as shown in the previous chapter, these formulas apply exclusively in sugar and final molasses-producing plant.

Normally, Brazilian mills separate part of the mixed juice to be sent to the distillery, or else the juice from the first set of milling (primary juice) is sent to sugar production and the juice from the other set of mills (secondary juice) is sent to ethanol production (**Figure 10.1**).

The model presented in **Figure 10.1** can be used in sugar and ethanol mills, as is the case of Brazilian companies, and the suggested formulas for sugar and ethanol recovery work together for any production mix of sugar and ethanol. The formulas simulate variations in the quality of the raw material, variations in the production mix, variations in the total reducing sugars (TRS) losses (wastewaters, bagasse, filter cake, and undetermined), and the distillery efficiency (fermentation and distillation). They create scenarios that guide the selection of the best alternative for maximizing the company's industrial efficiency and profitability. Theoretical yield formulae are also useful for the evaluation of cane quality and can be incorporated into the cane payment system.

At present these formulae do not consider all the characteristics of the raw material that influence the results. Not included are indications of polysaccharides from post-burning and/or cutting cane deterioration (such as dextran), and cane pointers that evaluate natural polysaccharides as starch, organic acids, phenolic compounds, and oligosaccharides. Other quality indicators such as the ratio of reducing sugars to

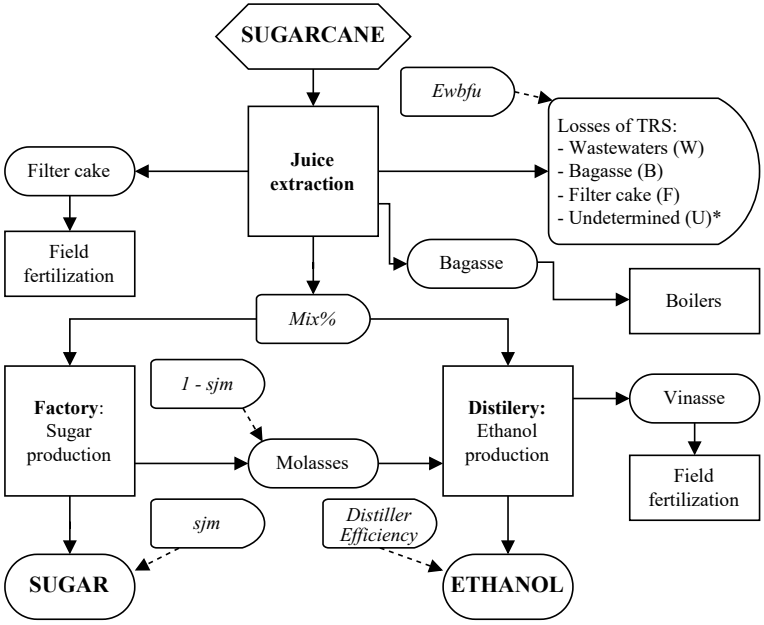

Figure 10.1 – Simultaneous production of sugar and ethanol from sugar cane.

ash in the juices, low moisture cane, soil, and trash impurities from mechanized loading or mechanized harvesting are omitted from the formulae. In formulae for sugar/ethanol factories, the final molasses stream is not relevant in terms of sugar losses since it is sent to ethanol production and its losses are computed in the distillery efficiency. The sugar streams that appear in the usual stages of manufacture can be used in different proportions (mix%) to produce sugar and ethanol.

10.1 Theoretical Sugar Yield (TSY)

Assuming, for didactic purposes only, a separate flow for sucrose or pol % cane and another for reducing sugars % cane for the calculation of the "theoretical sugar yield" TSY, and the "theoretical ethanol yield" TEY (**Figure 10.2**).

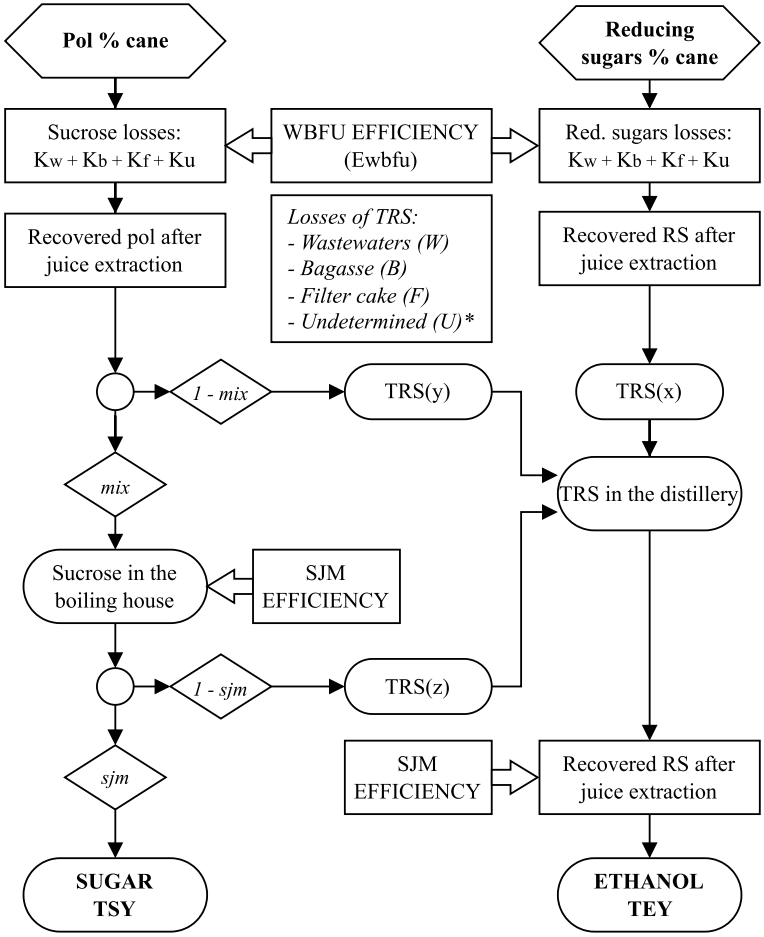

Figure 10.2 – Simplified flowchart for calculating theoretical yields of sugar and ethanol. The portions (x), (y), and (z) represent the amount of sugar sent to the distillery according to the percentage of cane used to manufacture sugar (Mix).

For one ton of cane, the theoretical sugar yield (in kg units/t of cane) can be calculated as:

$$TSY = 10 * Pol\ \%\ cane * Mix / 100 * WBFU / 100 * SJM / 100$$

Where:

Mix: the percentage of total sucrose or pol in cane used for sugar production. *It can be any value between zero and 100, according to the capacities of the sugar factory and the distillery. If "Mix" equals zero, only ethanol will be produced, and if the "Mix" value is 100%, sugar, and residual ethanol (from final molasses only) will result.*
WBFU: efficiency considering losses of sugar in wastewater (W), bagasse (B), filter cake (F), and undetermined (U).
SJM: boiling house recovery (%) as formulated by Deerr (1911).

The SJM recovery should use sugar purity (S), defined as 100%, juice or syrup purity (J), and molasses true purity (M). The syrup purity may or may not be considered equal to the purity of the cane juice extracted in the press.

SJM = 100 ∗ 100 ∗ (Syrup purity - Molasses purity) / (Syrup purity ∗ (100 - Molasses purity))

The SJM formula indicates the percentage of sucrose that can be crystallized as a function of syrup (or juice) purity and molasses purity.

The formula [10 ∗ Pol % cane ∗ WBFU/100 ∗ Mix/100] results in the theoretical mass of sucrose in the syrup from 1000 kg of cane, once the losses in the previous steps (WBFU) were deducted. This result must be multiplied by the fraction of SJM recovery considering the purity of the syrup and the true purity of the final molasses. For practical purposes, when the syrup's purity is unknown, either the press juice purity or the mixed juice purity can be used. The molasses purity can be the measured molasses true purity or an assumed target value for final molasses purity.

10.2 Theoretical Ethanol Yield (TEY)

If reducing sugars present in the cane supply undergo the same proportional losses as pol or sucrose in the manufacture of sugar and ethanol, the same WBFU efficiency can then be applied to estimate the ethanol yield (L/t cane). In a plant with an attached distillery, the ethanol is manufactured from (x) the original reducing sugars of the cane, (y) the sucrose sent to produce the ethanol (1 - Mix/100) and (z) the sucrose retained in the molasses (1 - SJM/100). Therefore:

x) Original reducing sugars from cane minus losses of sugar and ethanol in the common phase of sugar production (kg/t cane)

TRSx = 10 * Reducing sugars % cane * WBFU / 100

y) Sucrose from cane used for ethanol production (kg/t cane)

TRSy = 10 * Pol % cane / 0.95 * WBFU / 100 * (1 - Mix /100)

z) Sucrose retained in molasses (kg/t cane)

TRSz = 10 * Pol % cane/ 0.95 * WBFU / 100 * Mix / 100 * (1 - SJM / 100)

The total TRS sent to the distillery is the sum of the three parts (x, y, and z) of TRS.

TRS in the distillery (kg/t cane) =
10 * Reducing sugars % cane * WBFU / 100 +
10 * Pol % cane / 0.95 * WBFU/ 100 * (1 - Mix /100) +
10 * Pol % cane / 0.95 * WBFU/ 100 * Mix /100 * (1 - SJM /100)

Simplifying:

TRS in the distillery (kg/t cane) = 10 * Pol % cane / 0.95 * WBFU / 100 * (1 + 0.95 * Reducing sugars % cane / Pol % cane - Mix / 100 * SJM / 100)

Multiplying the previous result by 0.6480 (the stoichiometric factor for converting TRS into ethanol) and by the Overall Distillery Efficiency (ODE) fermentation and distillation, the Theoretical Ethanol Yield (TEY) in liters per ton of cane is obtained by:

TEY= 10 * Pol % cane / 0.95 * WBFU / 100 * (1 + 0.95 * Reducing sugars % cane / Pol % cane - Mix / 100 * SJM / 100) * 0.6480 * DOE / 100

Where:

Mix: percentage of total sucrose or pol in cane used for sugar production (between zero and 100%).
WBFU: efficiency considering losses of total reducing sugars (TRS) in wastewater (W), bagasse (B), filter cake (F), and undetermined (U),
SJM: boiling house recovery (%) by Noel Deerr,
DOE: the distillery overall efficiency for fermentation and distillation of ethanol,

The same result can be obtained by:

TEY (L/t cane) = (10 * TRS * WBFU / 100 - TSY / 0.95) * 0.6480* DOE / 100

10.3 Expected and Relative "Total Recovery"

From the theoretical yields of sugar and ethanol, it is possible to calculate what would be the overall factory efficiency if the industrial unit operated within the defined parameters of efficiency and quality of the raw material.

Theoretical total reducing sugars (TRS) in the products

TRS corresponding to the theoretical yields of sugar and ethanol = Total crushed cane (t) * (TSY / 0.95 + TEY / 0.6480)

Where:

TSY: Theoretical Sugar Yield (kg/t cane)
TEY: Theoretical Ethanol Yield (L/t cane)

Note that 0.95 and 0.6480 are stoichiometric factors for the conversion of sucrose into TRS and ethanol into TRS.

Theoretical Total Recovery

The ratio between the total TRS of the manufactured products and the total TRS of the cane indicates the "theoretical factory and distillery efficiency" arbitrated by the company as a target or standard to be achieved.

Expected factory and distillery efficiency = 100 * TRS corresponding to the theoretical sugar and ethanol / TRS corresponding to the sugar and ethanol produced

Note: This result indicates the industrial efficiency that should be achieved if the company operates with the efficiencies arbitrated as a target or standard used in the calculation of TSY and TEY.

Relative Total Recovery

The relationship between the total TRS of the manufactured products (sugar and ethanol) with the total TRS of the theoretical products indicates whether the company worked above or below the standards established as targets.

Relative "Total Recovery"= 100 ∗ (TRS corresponding to the sugar and ethanol produced) / (TRS corresponding to the theoretical yields of sugar and ethanol)

Through the relative theoretical industrial efficiency, calculated in terms of TRS, it is possible to compare the performance of plants technically, even with different characteristics, since for each company its targets have been defined. For the calculation of TSY and TEY, standard efficiencies must be established according to the production profile of each company. Variations of the profile include it being a sugar and ethanol plant, an autonomous distillery, or a plant that produces sugar and sends the molasses to other companies.

10.4 Estimating molasses production

Several calculation criteria can be used to estimate the amount of molasses produced in the sugar and ethanol manufacturing process. The calculations presented below are theoretical and should not replace physical measurements for determinations of mass balances of the process. The formulas can be applied in simulation models of sugar and molasses production, as they can assist in the creation of scenarios for process management.

When sugar production is known

Considering that syrup enters the boiling house and sugar and molasses leave, the total soluble solids (brix) in the syrup minus the solids (mainly sucrose) recovered in the sugar will result in the total solids in the molasses produced. The total solids in the molasses (or Brix) can be divided by the Brix % molasses to estimate the theoretical total of produced molasses.

Soluble solids in molasses = Soluble solids in syrup - Solids in the produced sugar

Estimated molasses production = 100 * Total solids or Brix in molasses / Brix % molasses

This calculation requires knowledge of the total brix in the syrup, which is not commonly measured in sugar factories. A practical alternative is to estimate this total brix value from the known cane brix and the WBFU efficiency:

Soluble solids in molasses = Feedstock cane * Brix % cane / 100 * WBFU Efficiency / 100

The inclusion of the total of undetermined losses in the process steps up to the syrup (the WBFU losses) is one weakness in this calculation. Another is the inaccuracy inherent in the estimation of Brix % cane.

The estimated yield of molasses per ton of cane or 50 kg bag of sugar is the common way of expressing the results in Brazilian mills.

SJM recovery to estimate the sugar production

The total sucrose in the syrup multiplied by the fraction SJM recovery gives an estimate of the total sugar produced. Conversely, the division of the total sugar produced (expressed as sucrose) by the SJM efficiency yields a value for the total sucrose in the syrup. Taking the lone terms Sugar, Syrup, and Molasses as denoting mass values, and pol as an estimation of sucrose:

Sucrose in syrup = Sugar / (SJM / 100)

Syrup = Sucrose in syrup / (Sucrose % syrup / 100)

Total brix in syrup = Syrup * Brix % syrup/ 100

Substituting for Syrup:

Total brix in syrup = Sugar * Brix % syrup / (Pol % syrup * SJM / 100)

Molasses = 100 ∗ Sugar ∗ (Brix % syrup / (Pol % syrup ∗ SJM / 100) – 1) / Brix % molasses

Replacing and simplifying again:

Molasses (kg) = 100 ∗ Sugar (kg) / Brix % molasses ∗ ((100 - Molasses purity) / (Syrup purity - Molasses purity) -1)

Applications of this formula use apparent purity values for syrup and true purity values for molasses, following the SJM formula requirements.The application of this equation for estimating the amount of molasses depends on the accuracy of the analytical results, that is, sampling and analysis of syrup and molasses. It should not be used for industrial process control, but it can be applied in scenario simulation systems and the definition of work targets.

10.5 Example of creating a scenario

The following calculations will create a scenario to estimate the sugar and ethanol produced from a given mass of cane. The data used in this example are fictitious, but represent a typical set.

Data input

Cane to be milled	2,350,000 t
Pol % cane	14.53%
Fiber % cane	12.66%
RS % cane	0.54%
Mix	66.70%
WBFU Efficiency	92.50%
DOE	88.40%
Syrup apparent purity	87.07%
Molasses true purity	47.00%
Brix % molasses	82.00%

Where:

RS: Reducing Sugars (glucose and fructose)
TRS: Total Reducing Sugars (glucose + fructose + sucrose/0.95)
Mix: percentage of total sucrose or pol in cane used for sugar production (between zero and 100%)
WBFU Efficiency: considering losses of TRS in Wastewater, Bagasse, Filter cake, and Undetermined. It can vary from 88% to 94%
SJM: boiling house recovery (%) by Noel Deerr
DOE: Distillery Overall Efficiency (%) (fermentation and distillation)

When assuming the juice purity, it must be coherent with the pol % cane as used in a simulation. Juice purity has a significative regression with pol % cane, as, in the example below, from a Brazilian group of mills.

$$\text{Juice purity} = -0.175 * \text{Pol \% cane}^2 + 6.8 * \text{Pol \% cane} + 25.2$$

If reducing sugars % cane is not known, it can be estimated using the Consecana (Brazil) equation as a function of extract juice purity from the press.

$$\text{RS \% juice} = (3.641 - 0.0343 * \text{Juice purity})$$

$$\text{RS \% cane} = \text{RS \% juice} * (1 - 0.01 * \text{Fiber \% cane}) * (1.0313 - 0.00575 * \text{Fiber \% cane})$$

See Section 7.3.7 for details.

Example calculations

$$\text{Total Reducing Sugars \% cane} = 10 * (\text{Pol \% cane} / 0.95 + \text{RS \% cane})$$
$$= 10 * (14.53 / 0.95 + 0.54) = 15.8347\%$$

Taking "Cane" as the mass of cane, in metric tonne (t) units:

Total pol in cane = 10 * Cane * Pol % cane
= 10 * 2,350,000 * 14.53 = 341,455,000 kg

Total RS in cane = 10 * Cane * RS % cane
= 10 * 2,350,000 * 0.54 = 12,690,000 kg

Total TRS in cane = 10 * Cane * Total Reducing Sugars % cane
= 10 * 2,350,000 * 15.8347 = 372,115,450 kg

Sucrose % molasses = Molasses purity * Brix % molasses / 100
= 47.00 * 82.00 / 100 = 38.54%

SJM = 100 * 100 * (Syrup purity - Molasses purity) / (Syrup purity * (100 - Molasses purity))
= 100 * 100 * (87.07 - 47.00) / (87.07 * (100 - 47.00)) = 86.83%

WBFU Lost = 100 – WBFU Efficiency
= 100 - 92.50 = 7.50%

"WBFU Lost" is the TRS lost in Wastewater, Bagasse, Filter cake, and Undetermined.

Calculation of the theoretical sugar

Total theoretical sugar = 10 * Pol % cane * WBFU/ 100 * SJM / 100
= 10 * 14.53 * 92.50 / 100 * 86.83 / 100 = 116.70 kg/t cane total

Theoretical Sugar Yield = 10 * Pol % cane * WBFU/ 100 * SJM / 100 * MIX / 100
= 10 * 14.53 * 92.50 / 100 * 86.83 / 100 * 66.70 / 100 = 77.84 kg/t cane for sugar

Sugar to be produced = Cane * Theoretical Sugar Yield = 2,350,000 * 77.84 = 182,924,000 kg

Cane for sugar = Sugar to be produced / Theoretical Sugar Yield
= 182,924,000 / 77.84 = 1,567,472.151 t

Cane for sugar % total = 100 * Cane for sugar / Cane
= 100 * 1,567,472 / 2,350,000 = 66.70%

Pol total cane for sugar = Cane for sugar * Pol % cane / 100
= 1,567,472 * 14.53 / 100 = 227,753,704 kg

Factory efficiency = 100 * Sugar to be produced / Pol total cane for sugar
= 100 * 182,924,000 / 227,753,704 = 80.32%

Calculation of the theoretical ethanol

Cane for ethanol = Ethanol to be produced / Theoretical Ethanol Yield
= 86,879,500 / 36.97 782,527.849 t

Cane for ethanol % total = 100 * Theoretical Sugar Yield / Total theoretical sugar
= 100 * 77.84 / 116.70 = 33.30%

Theoretical Ethanol Yield = (10 * Total Reducing Sugars * WBFU / 100 - Theoretical Sugar Yield/ 0.95) * 0.6480 * Overall Distillery Efficiency/100
= (10 * 15.8347 * 92.5 / 100 - 77.84/ 0.95) * 0.6480 * 88.40 / 100 = 36.97 L/t cane total

Ethanol yield cane for ethanol = 10 * Total Reducing Sugars * WBFU / 100 * Overall Distillery Efficiency / 100 * 0.6480
= 10 * 15.8347 * 92.50/ 100 * 88.40 / 100 * 0.6480 = 83.90 L/t of cane for ethanol

Ethanol to be produced = Cane * Theoretical Ethanol Yield
= 2,350,000 * 36.97 = 86,879,500 L

Calculation of theoretical molasses

Theoretical Molasses Yield = 100 * Theoretical Sugar Yield / Brix % molasses * ((100 - Molasses purity) / (Syrup purity - Molasses purity) - 1)
= 100 * 77.84 / 82.00 * ((100 - 47.00) / (87.07 - 47.00) - 1) = 30.63 kg/t cane total

Molasses to be produced = Theoretical Molasses Yield * Cane
= 30.63 * 2,350,000 = 71,980,500 kg

Yield total molasses = Molasses to be produced / Cane for sugar
= 71,980,500 / 1,567,472 = 45.92 kg/t cane for sugar

Yield total molasses (using the equation) = 100 * Theoretical Sugar Yield / Syrup purity * ((100 - Molasses purity) / (Syrup purity - Molasses purity) - 1)
= 100 * 77.84 / 87.07 * ((100 - 47.00) / (87.07 - 47.00) - 1) = 45.92 kg/t cane total

Molasses, ethanol, and total reducing sugars (TRS)

Direct ethanol from cane = Cane for ethanol * Ethanol yield cane for ethanol
= 782,527.849 * 83.9 = 65,654,087 L

Residual ethanol from molasses = Ethanol to be produced - Direct ethanol from cane
= 86,879,500 - 65,654,087 = 21,225,413 L

Residual ethanol yield total cane = Residual ethanol from molasses / Cane to be milled
= 21,225,413/ 2,350,000 = 9.03 L/t cane total

Residual ethanol yield molasses = 1000 * Residual ethanol / Theoretical Molasses Yield
= 1000 * 21,506,119.46 / 30.63 = 294.88 L/t molasses

TRS molasses retained sucrose = Sugar to be produced * (1 - SJM/ 100) / 0.95
= 182,924,000 * (1 - 86.83/ 100) / 0.95 = 25,359,043 kg

Total RS after WBFU losses = Total RS in cane * MIX / 100 * WBFU / 100
= 12,690,000 * 92.5 / 100 * 66.7 / 100 = 7,829,413 kg

Total of TRS in molasses = TRS molasses retained sucrose + Total RS after WBFU losses
= 25,359,042.95 + 7,829,413 = 33,188,456 kg

TRS % molasses = 100 * Total of TRS in molasses/ Molasses to be produced
= 100 * 33,188,456/ 71,980,500 = 46.11%

Residual ethanol = Total of TRS in molasses * 0.6480 * DOE = 33,188,456 * 0.6480 * 88.4
= 21,506,119 L

Total Recovery

Sugar as TRS = Sugar to be produced / 0.95
= 182,924,000 / 0.95 = 192,551,579 kg

Ethanol as TRS = Ethanol to be produced / 0.6480
= 86,879,500 / 0.6480 = 134,073,302 kg

Total of TRS in products = Sugar as TRS + Ethanol as TRS
= 192,551,579 + 134,073,302 = 326,624,,881 kg

Total Recovery (OR) = 100 * Total of TRS in products / Total TRS in cane
= 100 * 326,624,881 / 372,115,450 = **87.78%**

TRS sugar % TRS total products = 100 * Sugar as TRS / Total of TRS in products
= 100 * 192,551,579 / 326,624,881 = 58.95%

TRS ethanol % TRS total products = 100 * Ethanol as TRS / Total of TRS in products
= 100 * 134,073,302 / 326,624,881 = 41.05%

Corrected factory yield (RIC, MIC-IAA 1981)

Note: The explanation for the next calculation is described in Chapter 18 "Corrected sugar and ethanol yield".

Production of standard sugar (99.3%) and anhydrous ethanol ($99.3\%_{m/m}$)

Standard sugar 99.3% = Sugar to be produced / 0.993
= 182,924,000 / 0.993 = 184,213,494 kg

Anhydrous ethanol $99.3\%_{m/m}$ = Ethanol to be produced * 1.00246
= 86,879,500 * 1.00246 = 87,249,607 L

Considering the true purity of molasses as 40% (MIC-IAA)

Total RIC = 0.8281 * Standard sugar 99.3% + 1.4728 * Anhydrous ethanol $99.3\%_{m/m}$
= 0.8281 * 184,213,494 + 1.4728 * 87,249,607= 281,048,416 kg

RIC **Corrected Factory Yield** = Total RIC / Cane
= 281,048,416 / 2,350,000 = 119.60 kg/t cane

Overall Factory Recovery = Total RIC / Total pol in cane
= 281,048,416 / 341,455,000 = **82.31%**

Cane for sugar and ethanol

Cane for sugar = Standard sugar 99.3% / Corrected Factory Yield
= 184,213,494 / 119.6 = 1,540,246.605 t

Cane for ethanol = Cane to be milled - Cane for sugar
= 2,350,000 - 1,540,246.605 = 809,753.395 t

Cane for sugar % total cane = 100 * Cane for sugar / Cane to be milled
= 100 * 1,540,246.605 / 2,350,000 = 65.54%

Cane for ethanol % total cane = 100 - Cane for sugar % total cane
= 100 - 65.54 = 34.46%

Theoretical yield of ethanol

Residual anhydrous = 5.8333 * Standard sugar 99.3% / 50
= 5.8333 * 184,213,494 / 50 = 21,491,451 L

Residual anhydrous yield = Residual anhydrous ethanol / Cane for sugar
= 21,491,451 / 1 540,246.605 = 13.95 L/t cane

Anhydrous ethanol direct from cane = Anhydrous ethanol $99.3\%_{m/m}$ - Residual anhydrous
= 87,249,607 - 21,491,451 = 65,758,156 L

Direct anhydrous ethanol cane yield = Anhydrous ethanol direct from cane / Cane for ethanol
= 65,758,156 / 809,753.395 = 81.21 L/t cane

11 Juice extraction by mills or diffusers

In the process of extracting juice from cane, the most important analytical determination is the percentage of pol in bagasse. Using this value, along with the mass of cane, the pol % cane, and an estimate of the mass of bagasse, allows the efficiency of the equipment used for extraction to be determined. The moisture % bagasse is also important for the estimation of the mass of bagasse by a fiber balance and for the estimation of the calorific value of bagasse fed to the factory bagasse steam boilers, which is of great interest to boiler supervisors.

Analyzing the juices extracted in each mill of the tandem does not affect industrial performance, but it provides useful information for managing the milling or diffuser/mill process. That information is especially relevant when a poor overall extraction rate is occurring.

11.1 Prepared cane

A sampling of the prepared cane should be done exclusively to determine the "cane preparation index", which is the ratio between the saccharimeter readings of the shaker and the cold extractor (wet disintegrator).

Sampling of prepared cane

A sampling of the cane prepared in the factory by the cutter knives and shredder hammers should be done routinely once a day. Additional sampling could be actioned when changes in the visual appearance of the bagasse are observed or immediately after a doubtful pol % bagasse result.

The sample should be manually collected for 15 minutes with the aid of a suitable tool along the conveyor belt at the full depth of the prepared cane bed. The full-depth sample is required to minimize the effects of particle segregation. The sample is then homogenized manually and a

subsample is taken for analytical determinations. The laboratory manual is followed to ensure proper procedures. The dilution for bagasse samples is usually 1:3, and saccharimeter readings are taken from two samples after the shaking procedure, and one after the wet disintegrator procedure.

Example of the calculations for cane preparation index (CPI)

Saccharimeter readings:

Saccharimeter reading shaker 1	SRs1 = 9.40 °Z
Saccharimeter reading shaker 2	SRs2 = 9.35 °Z
Saccharimeter read. wet disintegrator	SRe = 10.25 °Z

Cane preparation index = 50 * (SRs1 + SRs2) / SRe
= 50 * (9.40 + 9.35) / 10.25 = 91.5%

Interpretation of cane preparation index (CPI)

The result of the cane preparation index (CPI) should be interpreted together with the inspection of the visual and tactile aspects of the prepared cane. It may be between 85% and 92% depending on the type and efficiency of the cane preparation systems.

An experienced operator can visually assess the quality grade of cane preparation and identify necessary adjustments to the hammers and knives in the existing installation.

11.2 Juices from the mill or diffuser

Several types of juices can be sampled during the extraction system of the sugar and ethanol production facility (**Figure 11.1**).

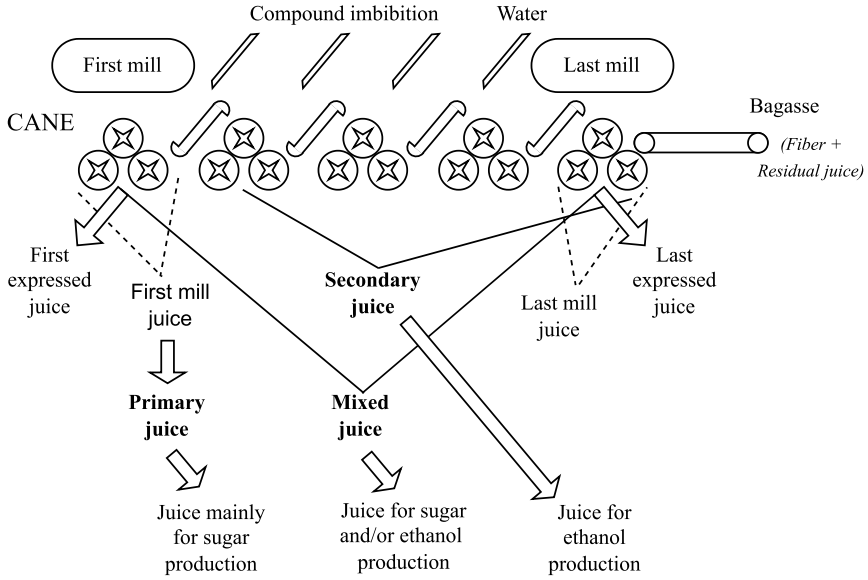

Figure 11.1 – Diagram of different types of sugarcane juice that can be produced in a five-mill milling train.

First expressed juice and primary juice

First-expressed juice is the first juice extracted from the sugarcane in the first two rolls of the first milling set, without imbibition or bagasse return. In the conception of modern mills, the sampling of this juice has become impractical, except in Australia, where it is sampled for use in their cane payment formula and for factory control. The primary juice is the juice extracted in the first milling set and is more commonly sampled than the first expressed juice. When there is the separation of juices in the mill, this juice is usually sent to sugar production.

When there is no return of bagasse and intermediate juices onto the prepared cane, the brix % primary juice presents a significative linear correlation (R^2>0.85) with the brix % extract juice from the laboratory press. If the linear regression is not significant, it may indicate that

the sampling, analysis, or calculations of the primary juice the cane, or both, are not being conducted correctly.

Secondary juice

The secondary juice is the juice from the second and other milling sets and it has a lower brix and lower purity than the primary juice. When the juices are separated at the plant, depending on the desired sugar/ethanol production mix, this juice can be sent to the production of ethanol and may be mixed with molasses.

Residual juice and last expressed juice

Residual juice is the juice extracted in the last mill system. The last-expressed juice is the juice extracted from the cane in the last two rolls of the last milling set and it is often assumed that the purity (pol % brix) of this juice is equal to that of the juice retained in the final bagasse. In some situations, there may be confusion between last-expressed juice and residual juice.

Mixed juice

Mixed juice is the mixture of juices extracted in all milling units or the total juice extracted in diffuser/mill systems. When there is separation of juices in the mill, or where juice from a mill before a bagasse diffuser is separated from the diffuser juice, there can be no mixed juice. for a cane system, there will always be a mixed juice.

Selection of juices for sugar and ethanol production

Several sugar and ethanol factories select the primary juice (from the first milling unit) for the manufacture of sugar and the secondary juice for ethanol. The higher purity of primary juice makes it the better choice for sugar production. However, when there is insufficient primary juice for sugar production, some secondary juice is sent along

with the primary juice to increase sugar production at the cost of lowering ethanol production.

11.3 Sampling of juices

Sampling of the mill juices is often an essential activity in industrial process control. However, it is essential for plants that use in their calculations the fundamental equation (Milled cane + Imbibition water = Mixed juice + Bagasse).

Traditionally, the first expressed juice or primary juice can be sampled and analyzed to indicate the quality of the raw material being received. Also sampled and analyzed are mixed juice, and, when using a diffuser for extraction, the residual juice, or the last expressed juice could be sampled.

Where appropriate, the flows of "Juice for sugar" and "juice for ethanol" could be sampled instead of "primary juice" and "secondary juice". This is to establish the quality of these juices and provide guidance to the process supervisors.

When the mass of "juice for sugar production" is measured by weighing machines or flow meters (the latter are not essential and not recommended), the "Boiling House Recovery" (BHR) can be calculated by the relationship between the total pol (sucrose) in the sugar produced plus the pol in the molasses produced with the total pol in the juice sent to sugar production. The BHR indicates the losses between mixed juice and sugar production. If any material from the sugar factory (syrup, massecuite, masse, magma) is discharged or sent to the distillery, it will be indicated by the decrease in BHR. The percentage ratio between BHR and SJM recovery results in "boiling section efficiency".

The recommended frequency of routine juice sampling and analysis should be about every four hours. With optional continuous sampling

and proper sample conservation, analytical determinations should be performed approximately every eight hours.

11.4 Analysis of juice

Brix and pol should be determined primarily in the juices from the mill or diffuser. For sugar/ethanol plants that use the "fundamental equation" for their mass balance, the determination of reducing sugars % mixed juice should also be included.

The calculations described below for mixed juice are the same for the other juices in the sugar/ethanol factory process.

Data for a mixed juice analysis example

Saccharimeter reading	52.64 °Z
Brix % mixed juice	15.4%

Regression equation for mixed juice density

$$\text{Juice density} = 0.015726 * \text{Brix \% mixed juice}^2 + 3.81451 * \text{Brix \% mixed juice} + 997.36$$
$$= 0.015726 * 15.4^2 + 3.81451 * 15.4 + 997.36 = 1059.835 \text{ kg/m}^3$$

This quadratic equation of juice density versus juice brix (at 20°C) is valid for the range of juice brix between 10% and 26%. The density of this juice in the ICUMSA table is 1059.837 kg/m^3.

Pol % mixed juice calculation example

$$\text{Pol \% mixed juice} = \text{Saccharimeter reading} * (0.2605 - 0.0009882 * \text{Brix \% mixed juice})$$
$$= 52.64 * (0.2605 - 0.0009882 * 15.4) = 12.91\%$$

Purity of mixed juice calculation

Purity mixed juice = 100 ∗ Pol % mixed juice / Brix % mixed juice
= 100 ∗ 12.91 / 15. = 83.8%

The purity results value should be expressed with only one decimal place.

11.5 Reducing sugars and TRS determinations

Only for sugar/ethanol plants that do not have a core/press system and have to use the "fundamental equation" (the mass balance expression.[cane + imbibition water = mixed juice + bagasse], it will be necessary to determine the TRS % mixed juice. The analytical procedures of TRS analysis by the "Lane & Eynon Method" can be found in various laboratory manuals. The calculations are described below in the item corresponding to the mash (wort, must).

All components of the following calculations must be mass in kilograms (kg) or tons (t):

Milled cane + Imbibition water = Mixed juice + Bagasse

Mixed juice = Milled cane + Imbibition water – Bagasse

Since the amount of fiber that enters the mill or diffuser with the cane is almost the same amount of fiber that leaves the mill in the bagasse, we have:

Bagasse = Milled cane ∗ Fiber % cane / Fiber % bagasse

Total TRS in mixed juice = Mixed juice ∗ TRS % mixed juice / 100

Total TRS in bagasse = Bagasse ∗ TRS % bagasse/ 100

See the determination of the TRS % bagasse in the following item "Bagasse".

Total TRS in cane = Total TRS in mixed juice + Total TRS in bagasse

TRS % cane = 100 ∗ Total TRS in cane / Milled cane

TRS determination in mixed juice

TRS % mixed juice can be determined directly by titration (Lane, 1923), by chromatography, or estimated by the following recommended equation:

TRS % mixed juice = Pol % mixed juice / 0.95 + Reducing sugars % mixed juice

While it is admitted that pol % mixed juice is not exactly equal to sucrose % mixed juice, this assumption is acceptable for this type of calculation.

The RS % mixed juice must be determined analytically. It is also not recommended to use the Consecana (Brazilian cane payment system) equations, which consider reducing sugars as depending on the purity of the mixed juice, or other equations. See more details in the chapter headed "Fundamental Equation".

11.6 Other analytical determinations

The "juice for sugar production" (primary juice) may be analyzed for phosphate content (P_2O_5) as phosphate levels might have to be boosted to obtain good results from lime or lime-saccharate clarification. Starch and dextran determinations may indicate the need to use starch amylases and/or dextranase enzymes. Only analytical determinations that can help the conduction of the clarification and sugar crystallization processes should be routinely included.

In the "juice for ethanol production" (secondary juice) determination of sulfates (SO_2) may be required to check whether sulfites are at levels that may affect the development of alcoholic fermentation or the

inhibition of enzymes, as high sulfates can lead to an increase in the time of fermentation.

11.7 Sampling and analysis of final bagasse

The final bagasse is an important material to be analyzed to evaluate the extraction performance of the mill or diffuser and for the operation of the bagasse steam boilers. The analytical results of fiber % bagasse and pol % bagasse enable the calculation of the extraction of pol from the cane, the estimation of the amount of bagasse produced, and the losses of sugars (pol and TRS) during the extraction process. The moisture % bagasse, along with the fiber % bagasse, allows the calorific value of the bagasse to be estimated and used for boiler control.

Sampling of final bagasse

A sampling of the final bagasse from the mill or diffuser can be performed manually with the aid of a tool (fork or tweezers). The sample must be collected immediately after leaving the last milling set, across the entire width of the bagasse mat and at the full depth of the bagasse mattress.

This sample should be homogenized on-site, and a subsample placed in a small bucket with a lid. The subsampling and bagasse analysis must be performed immediately.

Although not a priority, this activity can be automated but requires proper conservation of the sample in a suitable closed container. The bagasse leaving the end of the milling process is still warm and has moisture of around 50%, both conditions favorable for the development of bacteria carried from the field and the loss of water by evaporation.

It is recommended that the routine sampling frequency should be four hours. Sampling at higher frequency increases the costs for the company without significantly changing the daily values of pol % bagasse

or pol extraction. Of more importance is a check of the daily trends of these indicators by using suitable graphs or charts.

Analysis of final bagasse

The final bagasse from the mill or diffuser should preferably be analyzed using the cold extractor or wet disintegrator method, as is done in all cane sugar and/or ethanol-producing countries.

The use of a hydraulic press for final bagasse analysis is justified only in exceptional situations when there is no wet disintegrator available or where there is an unfortunate over-capacity in the sugarcane laboratory

The mass of the bagasse subsample taken for drying in the Spencer oven or for analysis by the wet disintegrator needs to be only approximately the standard value but its exact value must be noted for inclusion in the calculations. The same procedure applies to the water added to the extractor cup. This procedure speeds up the analysis, avoiding errors that may occur when preparing to an exact standard weight.

Bagasse analysis calculation

Moisture analyzers with halogen heating technology have been used to determine the moisture % bagasse. They can give automatically fast, precise, and reliable results.

However, Spencer ovens are more commonly used to allow direct determination of moisture % bagasse. The recommended procedure is:

Tare the balance with the oven basket and weigh 50.0g $\pm$2.0g of the wet bagasse sample. After 30 min. in the Spencer oven, tare the balance with the basket and the dry sample. Discard the dry residue and return the basket to the scale. The value that appears on the scale display (in negative value) corresponds to the dry fraction mass.

Example of calculation:

Wet bagasse mass	50.7 g
Dry bagasse mass	25.8 g

Moisture % bagasse = 100 ∗ (1 - Dry mass / Wet mass)
= 100 ∗ (1 - 25.8 / 50.7) = 49.1%

An alternative procedure:

Data from wet and dry bagasse may include the mass of the oven basket. Working with the approximate mass of the bagasse sample: Tare the scale with the oven basket and weigh 50.0 g ±1.0 g of the bagasse sample. Tare the scale without the oven basket and weigh the basket + wet bagasse. After 30 minutes in the Spencer oven weigh the basket + dried bagasse.

Example of calculation:

Weight of the wet bagasse sample	51.1 g
Basket mass with wet sample	293.4 g
Basket mass with dried sample	267.2 g

Moisture % bagasse = 100 ∗ (Basket mass with wet sample - Basket mass with dried sample) / Weight of wet bagasse sample
= 100 ∗ (293.4 - 267.2) / 51.1 = 51.3 %

The bagasse moisture should be at satisfactory low levels to provide fast and efficient burning in the boilers. In a mill of six milling units, the final bagasse moisture is usually between 48% and 50%.

Example of bagasse analysis by the cold extractor (wet disintegrator)

Weight of the wet bagasse sample	103.12 g
Weight water added to the extractor cup	1005.00 g
Saccharimeter reading tube 200 mm	0.56 □Z
Moisture % bagasse	50.7%
Purity of the sample of residual juice	70.2%

Dilution factor of the bagasse in the extractor

Dilution factor = Water (g) / Bagasse (g) + 1
= 1005.00 / 103.12 + 1 = 10.7459

With exact standard weights of 100 g of bagasse and 1000 g of water, the "Dilution factor" is equal to 11 (1000 g of water divided by 100 g of bagasse + 1).

Important: Annotating or, better, receiving the weights of water and bagasse added to the extractor bowl in an electronic device (data collector with a bar code reader) facilitates and speeds up the analytical work. With the data collector device, it is possible to work with approximated weights of bagasse and water since the computer software will use these actual figures in calculations.

Example of the calculation of Fiber % bagasse

Saccharimeter reading tube 200 mm	0.56 □Z
Moisture % bagasse	50.7%
Purity of residual juice	70.2%
The bagasse dilution factor in the extractor	10.7459

Fiber % bagasse = (100 - Moisture % bagasse - Dilution factor * 26 * Saccharimeter readin g/ Purity of residual juice)/ (1 - 0.26 * Saccharimeter reading / Purity of residual juice)
= (100- 50.7 - 10.7459 * 26 * 0.56/ 70.2) / (1 - 0.26 * 0.56/ 70.2) = 47.17%

Example calculation of Pol % bagasse

Pol % bagasse = 0.26 * Saccharimeter reading * (Dilution factor - 0.01 * Fiber % bagasse)
= 0.26 * 0.56 * (10.7459 - 0.01 * 47.17 = 1.50%

Example calculation of Brix % bagasse

Brix % bagasse = 100 - Moisture % bagasse - Fiber % bagasse
= 100 - 50.7 - 47.17 = 2.13%

Example calculation of TRS % bagasse

For the calculation of TRS losses in bagasse and the TRS mass balance, it is necessary to determine TRS % bagasse, which can be performed by the well-proven Lane & Eynon titration method (1923). However, this methodology, although of high precision, requires expert technicians, and is laborious and time-consuming on a routine scale.

The Somogyi & Nelson method or chromatography techniques can be used, but they are also precise and laborious.

Another alternative is to determine the RS % bagasse by one of these methods, preferably Somogyi & Nelson, and to estimate the TRS % bagasse by:

TRS % bagasse = Pol % bagasse / 0.95 + RS % bagasse

Ionic chromatography (IC) can also be used to obtain sucrose, glucose, and fructose % bagasse and calculate the "total fermentable sugars" (TFS) in bagasse:

TFS % bagasse = Sucrose% bagasse / 0.95 + Glucose % bagasse + Fructose % bagasse.

Once the IC technology has been validated and approved, ionic chromatography can probably be used for the analysis of a wide variety of components in other process streams.

Estimating TRS % bagasse

In most cases, the cost invested in any of the options described above is not justified to simply calculate the loss of TRS in the bagasse.

The ratio of TRS/Pol in cane cane (glucosic coefficient) differs from that in bagasse. Losses and inversions of sucrose occur in the extraction process due to the action of the natural enzymes, mainly invertases, of sugarcane, and of microorganisms, mainly bacteria.

However, for practical purposes, when the TRS % bagasse is not known, it can be admitted that its TRS/Pol ratio is similar to that in the cane. The error of this assumption does not significantly affect the results for industrial control. This assumption reduces costs due to the direct determination of RS or TRS in the bagasse extract of the wet disintegrator. As well the direct determination is subject to many errors due to high dilution.

In a simplified way it can be assumed that:

TRS % cane / Pol % cane = TRS % bagasse / Pol % bagasse

TRS % bagasse = **1.04** ∗ Pol % bagasse ∗ TRS % cane / Pol % cane

The coefficient **1.04** was obtained in 2014 with data from a group of Brazilian sugar and ethanol mills that determined RS % bagasse by the Somogyi & Nelson method and TRS was estimated by:

TRS % bagasse = Pol % bagasse / 0.95 + RS % bagasse.

This factor represents an increase of 4% in the TRS % bagasse due to sucrose inversions that occur during the extraction of the juice in the mills or diffuser/mill systems. This subject needs to be further investigated, including the estimation of the TRS in filter cake.

Using the data from the previous examples for analysis of sugarcane and bagasse:

TRS % cane	15.77%
POL % cane	14.45%
POL % bagasse	1.50%

TRS % bagasse =1.04 ∗ Pol % bagasse ∗ TRS % cane / Pol % cane
= 1.04 ∗ 1.50 ∗ 15.77 / 14.45 = 1.70%

11.8 Sampling and analysis of filter cake

Usually, the filter cake is analyzed to determine the pol % filter cake and moisture % filter cake. The look of the filter cake and the feed mud to the filters provide important operational information to experienced operators.

Filter cake sampling

For rotary filters, sample cake should be sampled at several places along the entire length of the rotary drum. The sample should be collected from the cake discharge collection box in filter presses. If the filter cake pol values differ substantially from the established target value, sampling can be performed manually in the mixing box of all filters.

The frequency of cake sampling should be every four hours, in a routine manner, with immediate analysis of the cake, as it is highly perishable. Sampling can be automated to ensure continuous sampling, but automatic sampling of multiple individual rotary filters would be costly and automation is not a priority.

Analysis of the Pol % filter cake

When using 50 g of the filter cake sample in a 200 mL Kohlrausch flask, and then clarifying the mixture, the saccharimeter reading of the clear liquid in a 200 mm tube would correspond to the value of pol % filter cake.

If 25 g of the sample is taken, the saccharimeter reading in a 200 mm tube is doubled to obtain the value of pol % filter cake.

Analysis of moisture % filter cake

Some 50.0 g of the cake sample is dried in an electric oven with vented forced air circulation. The value of mass loss on drying value (g) is doubled to give the value for the moisture % filter cake.

Analysis of RS % filter cake

For Brazilian mills, it is necessary to know the TRS % filter cake to calculate the TRS mass balance and to assist in the evaluation of the "undetermined TRS losses % TRS in cane". The amount of sugar lost in the filter cake normally represents around 0.5% of the total TRS in the processed cane.

As described for bagasse analysis, the cost analytical determinations of TRS % filter cake is not justifiable for its use only in the TRS mass balance. The pol % filter cake is a sufficient indicator to evaluate the work of the filters.

It can be admitted, as was done for bagasse, that the ratio of TRS % cane to pol % cane is similar to that in the filter cake. In simplified form:

$$\text{TRS \% cane} / \text{Pol \% cane} = \text{TRS \% cake} / \text{Pol \% cake}$$

$$\text{TRS \% cake} = \text{Pol \% cake} * \text{TRS \% cane} / \text{Pol \% cane}$$

This is only approximately true, since sucrose losses and inversions occur during the treatment and purification of the juice, due to biological actions as previously mentioned for TRS in bagasse.

The TRS % filter cake estimated this way will probably be a lower value than that obtained by direct analytical determination. In this case, a fixed and arbitrary factor for percentage change can be included.

For practical purposes, the error of this assumption is marginal and does not significantly affect the results of industrial process control. It also reduces the costs of directly determining RS or TRS in the cake extract. As well, direct determinations are subject to many errors due to the high dilution involved.

Filter cake analysis calculation example

Data for example:

Produced filter cake (informed) 395.00 t
POL % filter cake (determined) 2.40%

TRS % filter cake (estimated) = Pol % filter cake * TRS % cane / Pol % cane
= 2.40 * 15.77 / 14.45 = 2.62%

Filter cake yield = 1000 * Filter cake produced (t) / Milled cane (t)
= 1000 * 395 / 13 398.324 = 29.5 kg/t of cane

12 Factory process calculations

There are two primary methods for calculating the control of the sugar and ethanol manufacturing process:

1. **Mass Balance**: This method is based on a fundamental equation: "The total mass of milled cane plus imbibition water equals the combined mass of mixed juice and bagasse".
2. **Sampling and Analysis of Cane**: This involves using the core/press or sampling the prepared cane for juice extraction (either through a mill or diffuser) or sampling and analyzing the first expressed juice, or the primary juice.

12.1 Mass balance

According to Rein (2007), nearly all sugar mills measure the amount of cane entering the mill and the sugar produced using weighbridges, which provide accurate measurements. However, in some mills, these are the only mass flows monitored.

This was the situation for Brazilian sugar and ethanol plants until the 1980s when the traditional "mass balance" approach was replaced by the "core/press" system. Over the past four decades, the core/press results have been used in hundreds of mills in Brazil (no statistic about this information was found).

To improve accuracy, Rein (2007) recommended using automatic batch scales for measuring raw juice and molasses. However, this practice is not advisable for Brazilian sugar and ethanol mills because these scales can contaminate the juice intended for ethanol fermentation.

Since implementing the National Alcohol Program (Proálcool) in 1975, the Brazilian sugar and ethanol industry has undergone significant technological transformations, including an urgent need to boost ethanol production. Consequently, Brazilian sugar mills began to

direct the primary juice toward sugar production while sending the secondary juice, along with molasses B (known as final molasses), to distilleries. This separation of juices at the mills made it challenging to use flow meters for calculating the mass balance.

In South Africa, the data of raw juice and bagasse analysis, and raw juice mass are used to determine the composition of the crushed cane, which is then compared with the figures obtained through direct sampling and analysis (Rein, 2007). The ratio of pol calculated from the mass balance compared to the pol obtained through direct analysis and cane mass is referred to as the Pol Factor. This value helps identify measurement issues or sucrose degradation problems:

Pol Factor = 100 ∗ (pol calculated from mass balance) / (pol from cane mass and direct analysis).

This indicates that if the "pol calculated from mass balance" is correct, then the pol % cane determined by direct analysis of cane (DAC) is inaccurate and needs to be "corrected" using the "Pol Factor". Otherwise, two different values of pol % cane will exist for the same cane.

12.2 Core/press

In Brazil, the success and acceptance of the core/press methodology, especially for chopped green cane, encouraged sugar and ethanol plants to replace traditional factory process control (mass balance) with the new technology. In the beginning, many studies and research were carried out since the new results regularly presented higher values for pol % cane and lower values for fiber % cane compared to the fundamental equation or mass balance.

The reduction in the calculated efficiency (Overall Recovery = Total sucrose in produced sugar % Total pol in milled cane) was a barrier at the beginning of the transition. Over time, it became apparent that the

new technology opened the possibility for improvements in searching for high-performance levels.

The initial drop in Overall Recovery (O.R.) posed challenges during the early transition phase. Eventually, it became clear that the new technology created opportunities for enhancements aimed at achieving higher performance levels.

12.3 Case study

In 2003, a sugar mill in Venezuela, without cane washing, was employing the core/sample methodology for cane payment , and the mass balance to calculate factory efficiency and sugar losses. The comparison of weekly averages of pol% cane obtained by both technologies in two crop seasons showed a correlated difference (**Figure 12.1**).

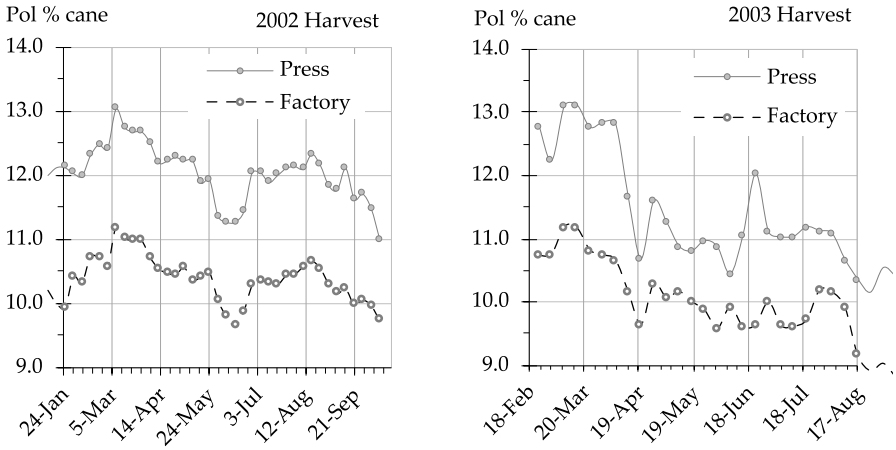

Figure 12.1 – Weekly averages of pol% cane at a Venezuelan sugar mill obtained by "mass balance" and "core/press" methods during the 2002 and 2003 crop seasons. The author gathered this data during a technical consultancy project.

The Overall Recovery calculated with "mass balance" was too low and when calculated with the figures of the "core/press" it was deemed unacceptable (**Table 12.1**). Other sugar mills in the same area presented values of pol % cane and fiber % cane more compatible with these results of core/press.

Table 12.1 – Comparison of mass balance with core/press for pol % cane and fiber % cane in two harvest seasons (2002 from Jan 12th to Oct 12th and 2003 from Feb 23rd to Sep 7th) at a Venezuelan sugar mill.

Results	Mass-balance	Core/press	Difference %
Fiber % cane 2002	15.64	13.56	-13
Pol % cane 2002	10.38	12.03	16
Fiber % cane 2003	15.52	13.14	-15
Pol % cane 2003	9.98	11.37	14
Overall Recovery (O.R.)	74.7	65.6	-12

O.R.= Total sucrose in produced sugar % total pol in milled cane (2003 harvest season)

It would be interesting to compare the mass balance results of pol and fiber % cane with those obtained from direct analysis of cane by the core/press method or from prepared cane as utilized in South African sugar mills, across different countries or regions.

Chopped green cane and the core/press

Most of the important research found on cane analysis is from the decades of 1970 and 1980 when the cane was burned, whole stalk hand cut, and mechanically loaded by grab loaders into trucks. The raw materials of that time had different characteristics of today's chopped green cane delivered to the mills.

With the use of core/press methodology in chopped green cane there is no delay between harvest and milling, no cane stored in the yard, and

no washing cane. The fiber % cane results include the trash (green and brown leaves, sheaths, tops of cane). The cane lab operates independently of the milling and can be verified by the independent growers. Key results, such as pol % cane, fiber % cane, and extracted juice purity, are used for field management, calculations of recoverable sugars for cane payment, and factory control. This multiple application ensures the quality and reliability of data.

12.4 Factory calculations for juice extraction

For sugar and ethanol manufacturing process control calculations, all mass data must be expressed in kilograms (kg) or tons (t) and volume data in liters (L) or cubic meters (m^3). The calculations in the following examples were performed in an MS-Excel® spreadsheet considering whole numbers (without decimals) for kilograms and liters. For tons and cubic meters three decimal places are used, although the following examples only show whole numbers.

For Brazilian mills and distilleries, the alcoholic strength by volume ($\%_{v/v}$), known in practice as GL grade (Gay Lussac), and alcoholic strength by mass ($\%_{m/m}$), must follow the ABNT (Brazilian Association of Technical Standards) methodologies, approved by INMETRO (Brazilian National Institute of Metrology).

From the results of the examples cited before (per day).

Cane quality example data (core/sampler):

Juice purity	86.8%
Fiber % cane	12.13%
Brix % cane	17.31%
Pol % cane	14.45%
RS % cane	0.56%
TRS % cane	15.77%

Milled cane	13,398.324 t
Imbibition water	4,689,000 L or kg

Bagasse and juice extraction example data:

Pol % bagasse	1.50%
Moisture % bagasse	50.7%
Fiber % bagasse	47.2%
Residual juice purity	70.2%

12.5 Milling calculations

The following calculations were performed step by step, totaling the accumulated harvest by summing the results in kilograms (kg) or tons (t) and volumes in liters (L) or cubic meters (m^3).

Totals in crushed sugarcane per day

Total fiber in cane = 10 * Milled cane * Fiber % cane
= 10 * 13,398.324 * 12.13 = 1,625,217 kg

Total brix in cane = 10 * Milled cane * Brix % cane
= 10 * 13,398.324 * 17.31 = 2,319,250 kg

Total pol in cane = 10 * Milled cane * Pol % cane
= 10 * 13,398.324 * 14.45 = 1,936,058 kg

Total TRS in cane = 10 * Milled cane * TRS % cane
= 10 * 13,398.324 * 15.77 = 2,112,916 kg

Bagasse

Brix % bagasse = 100 * Pol % bagasse / Residual juice purity
= 100 * 1.50 / 70.2 = 2.14%

Fiber % bagasse = 100 - Moisture % bagasse – Brix % bagasse
= 100 - 50.7 - 2.14 = 47.16%

TRS % bagasse = **1.04** ∗ Pol % bagasse ∗ TRS % cane / Pol % cane
= 1.04 ∗ 1.50 ∗ 15.77 / 14.45 = 1.70%

Bagasse yield = 1000 ∗ Fiber % cane / Fiber % bagasse
= 1000 ∗ 12.13 / 47.15 = 257.21 kg/t cane

Note that the coefficient **1.04** estimates an increase of 4% in the TRS % bagasse due to sucrose inversions occurring since the cane enters the process and during the extraction of the juice and exit of the final bagasse.

Totals in bagasse per day

Total of bagasse (kg) = Milled cane ∗ Bagasse yield
= 13,398.324 ∗ 257.21 = 3,446,183 kg

Total brix in bagasse = Total of bagasse ∗ Brix % bagasse / 100
= 3,446,183 ∗ 2.14 / 100 = 73,748 kg

Total pol in bagasse = Total of bagasse ∗ Pol % bagasse / 100
= 3,446,183 ∗1.50 / 100 = 51,693 kg

Total TRS in bagasse = Total of bagasse ∗ TRS % bagasse / 100
= 3,446,183 ∗ 1.70 / 100 = 58,585 kg

Totals in the extracted juice per day

Total brix in extracted juice = Total brix in cane - Total brix in bagasse
= 2,319,250 - 73,748 = 2,245,502 kg

Total pol in extracted juice = Total pol in cane – Total pol in bagasse
= 1,936,058 - 51,693 = 1,884,365 kg

Total TRS in extracted juice = Total TRS in cane - Total TRS in bagasse
= 2,112,916 - 58,585 = 2,054,331 kg

Pol and TRS extraction

Extraction of pol % pol cane = 100 * Total pol in extracted juice / Total pol in cane
= 100 * 1,884,365 / 1,936,058 = **97.33%**

Optionally:

Extraction of TRS % TRS cane = 100 * Total TRS in extracted juice / Total TRS in cane
= 100 * 2,054,331 / 2,112,916 = 97.23%

Reduced extraction by three formulas

Normally, the crop means of fiber % cane varies between 12.5% and 13.5%, by the core-press Brazilian sugarcane payment system (Consecana-SP). For this reason, calculating reduced extraction for fiber % cane of 12.5% is irrelevant, except where comparisons of milling train performance are to be made.

Below are formulas for calculating the **reduced extraction** (RE) after Noel Deer and Mittal.

RE by Noel Deerr = 100 - (100 - Pol extraction) * (100 - Fiber % cane) / (7 * Fiber % cane)
= 100 - (100 - 97.33) * (100 - 12.13) / (7 * 12.13) = 97.24%

RE by Mittal = 100-12.5/ Fiber % cane * (100 - Pol extraction)
= 100 - 12.5 / 12.13 * (100 - 97.33) = 97.25%

Total RE = 100 * (1 - Pol % bagasse / Fiber % bagasse)
= 100 * (1 - 1.50/47.15) = 96.82%

Imbibition (effective)

Imbibition is in kg units, Milled cane in t units:

Imbibition % cane = 0.1 * Imbibition water / Milled cane
= 0.1 * 4,689,000 / 13,398.324 = 35.00%

Imbibition % fiber = 100 * Imbibition water/ Total fiber in cane
= 100 * 4,689,000 / 1,625,217 = 288.52%

12.6 Efficacy of the milling tandem or diffuser

Informed example data

Available hours	24:00 h
Lost hours (total cane milling stops)	2:15 h
Nominal cane milling capacity	650 t/h

Tip: In the MS-Excel® worksheet cells with time data (*hh: mm*) should be formatted as [*h*]:*mm*.

Extraction performance calculations using effective hours

Effective hours of extraction = Available hours - Lost hours
= 24:00 - 2:15 = 21:45 h

Time utilization efficacy = 100 * Effective hours / Available hours.
= 100 * 21:45 / 24:00 = 90.63%

Milled cane per consecutive hour= Milled cane/ (24* Available hours for milling) = 13,398.324 / (24 * 24:00) = 558.26 t/h

Milled cane per effective hour= Milled cane/ (24* Effective hours of milling) = 13,398.324 / (24 * 21:45) = 616.02 t/h

Milled cane per effective 24 hours = 24 * Milled cane per effective hours
= 24 * 616.02 = 14,784 t of cane/24h

Efficacy of use of extraction equipment = 100 ∗ Milled cane per effective hour / Nominal milling capacity
= 100 ∗ 616.02 / 650 = 94.77%

Hourly production of bagasse = Total bagasse / (24 ∗ Effective hours ∗ 1000)
= 3,446,183 / (24 ∗ 21:45 ∗ 1000) = 158.45 t/h

13 Sugar and ethanol in-process

For simplicity, it is possible to assume that all pol (sucrose) in-retained in the sugar/ethanol factory equipment can be allocated to "sugar in the process". However, this assumption overestimates the result, since part of the sucrose in the process will not be crystallized, due to the formation of molasses.

The calculations below follow traditional sugar/ethanol factory technology principles. It is considered that there is the formation of molasses due to the material in process and the corresponding production of ethanol with this "virtual" molasses, besides the already produced molasses.

Importance of an accurate evaluation of the materials in the process

Rein (2017) considers that "a balance over one day is generally inaccurate and unreliable. The minimum time a reliable sugar balance can be obtained should be one week and only if the stock variation over the week is small".

However, Brazilian sugar/ethanol plants carry out the "closing" of the process balance daily at 6:00 h or 7:00 h and others at 24:00 h. Since sugar and ethanol plants are continuous processes, the daily volume and mass data will always be subject to measurement errors. These errors will be compensated for on the following day or when there is a general shutdown with the complete removal of the materials from the factory equipment.

If the sugar and/or ethanol material in the process has been overestimated, the production of the day must be under-compensated, and it may be even negative. This remains in the calculations accumulated in the season. On the other hand, when the product in-process is underestimated compared to the previous day, there will be an increase in production recorded for that day.

This means that excessive resources should not be made available to evaluate the "balance of sugar and ethanol in process". However, the balancing should not be neglected in that the estimates of production appear inconsistent in the daily bulletins.

Each company has the resources and expertise to carry out the survey of the products in the process. The following recommendations are generic and should be studied and refined to suit each sugar/ethanol factory.

13.1 Surveying the stocks of sugar in-process

Examples of the equipment to be considered in the sugar in-process calculations are the clarifiers, the syrup tanks, the vacuum pans for massecuites A, B, and C and their respective crystallizers; the magma tanks, the "seed deposit" vessels, the molasses tanks, and any sugar silos.

The volume of material in each sugar factory equipment item must be measured daily at closing time and the resulting volumes are transformed into mass (kg) through the density of the product (ICUMSA Table). The density (kg/m^3) can be also estimated with quadratic regression:

$$\text{Density } (kg/m^3) = 0.018223 * \text{Brix}^2 + 3.698409 * \text{Brix} + 998.2429$$

Where Brix is the mean brix of the previous day corresponding to each material in the considered process.

$$\text{Product in-process (kg)} = \text{Volume of product in-process (L)} * \text{Density } (kg/m^3) \ / \ 1000$$

Mass of brix and pol in the process

For each piece of equipment and corresponding product in-process, the following must be calculated:

Brix in-process (kg) = Product in-process (kg) ∗ Brix % product / 100

Pol in-process (kg) = Product in-process (kg) ∗ Pol % product / 100

Where "Brix % product" and "Pol % product" are the mean values of the closing day or period for each "product in process".

The sum of in-process brix (kg) and in-process pol (kg) of all the materials in-process will represent the total amount of brix and pol in the various equipment at the time of the survey.

Purity of the product in-process

Purity of the product in-process = 100 ∗ Pol in-process (kg) / Brix in-process (kg)

SJM formula used for estimation of sugar recovery

The proportion of sucrose that can be crystallized depends on the true purity of the final molasses and the purity of the material being processed; and can be estimated by the "SJM Recovery" formula. In this formula, sugar purity (S) is considered equal to 100% sucrose.

Recovery SJM = 100 ∗ 100 ∗ (In-process material purity - Molasses true purity) / In-process material purity ∗ (100 - Molasses true purity))

The molasses purity (M) must be the actual true purity, but this is not normally available, and therefore a default value has to be adopted. The default value can be the apparent value incremented by a small amount (e.g 2.5 units) approximating the typical difference between "true" and "apparent" purity at that factory.

The increment is higher for Australian conditions where the RS fraction of the impurities is low. The small error for this type of consideration

will be compensated throughout the season as the "virtual molasses" is produced, analyzed, and used.

In-process sugar calculation

The estimated amount of sugar in-process will be obtained by the SJM recovery on the mass of pol in-process in all the factory equipment plus the mass of sugar in the silos:

Sugar in-process (kg) = Pol in-process (kg) ∗ Recovery SJM /100 + Sugar in the silos (kg)

Note: "Sugar in the silos" represents all the sugar in the silos (kg) at the closing time of the sugar in-process calculation. The sugar in the silo, a "finished product", can be considered sucrose, since the multiplication of its mass by the pol % sugar is not necessary given the high inaccuracy in the estimation of the mass of the sugar in the silos.

In-process "virtual" molasses calculation

The products in-process at the sugar factory will produce sugar and molasses, here called "**virtual molasses**".

The amount of this "virtual molasses" can be estimated through the brix balance, subtracting from the total brix in the process (kg) the amount of pol that will be crystallized to obtain the mass of brix that would have been retained in the molasses.

This mass of brix (kg) divided by the mean Brix % of the produced molasses results in the mass of "virtual molasses" in-process at the sugar factory:

Virtual molasses in-process (kg) = 100 ∗ (Brix in-process - Pol in-process ∗ Recovery SJM / 100) / Brix % molasses

Example of a sugar in-process calculation

The following shows an example of the estimation of in-process sugar. The sum of total brix and pol in all equipment:

Sugar silo (finished sugar in-process)	60,000 kg
Total brix in process	733,661 kg
Total pol (sucrose) in-process	570,273 kg

In-process material purity = 100 * In-process pol / In-process brix
= 100 * 570,273 / 733,664 = 77.73%

Molasses purity (mean closing day) 52.67%

In-process SJM recovery = 100 * 100 * (In-process purity - Molasses purity) / (In-process purity * (100 - Molasses purity))
= 100 *100 * (77.73 - 52.67)/ (77.73 * (100 - 52.67)) = 68.12%

In-process sugar = 10 *Total pol in-process * In-process SJM recovery
= 10 * 570,273 * 68.12 = 388,453 kg

Total sugar in-process = In-process sugar + Sugar silos
= 388,453 + 60,000 = 448,453 kg

Sugar in-process yesterday 436,500 kg

Sugar in-process variation = 448,453 - 436,500 = **11,953 kg**

Theoretical molasses

For a sugar and ethanol mill, it is unnecessary to know the daily amount of molasses for factory control.

Where molasses is exported it could be determined directly by level readings on the storage tanks and by weighing the outgoing delivery transporters.

Alternatively, the mass of molasses today (kg) can be estimated by:

Total solids in molasses today = Total brix in-process today - In-process sugar today
= 733,661 – 388,453 = 345,208 kg

Brix molasses (ibnformed mean of closed day) 89.84%

Virtual molasses sugar factory today = 100 ∗ Total solids (brix) in molasses today/ Brix % molasses
= 100 ∗ 345,208 / 89.84 = **384,248 kg**

13.2 In-process ethanol evaluation

Examples of relevant equipment include clarifiers for the juice for ethanol production (secondary juice), fermentation vessels (receiving and fermenting mash and transferring fermenting wine to centrifuges), intermediate wine vats, wine tanks, and yeast treatment vats. The total volume of these materials should be multiplied by the average volumetric alcoholic strength ($\%_{v/v}$) of the centrifuged wine on the day.

When ethanol is present in the distillery's measuring tanks, it can be sent to the warehouse to be calculated as production, or the volume can be included as in-process ethanol.

In Brazil it is usual to assess the ethanol in-process at the closing time of each 24 hours as the sum of the in-process ethanol volumes in three process areas, namely: fermenters, yeast tanks, and molasses.

The following discussion outlines how the three areas are handled.

Ethanol in-process in the fermenters

The elements of the method of estimation of the ethanol volumes in process fermenters are shown in the expression:

Ethanol in-process in the fermenters = (Juice in the distillery's clarifiers + Mash or raw wine in the fermenters + Raw wine in tanks + Centrifuged wine in tanks) * Average volumetric alcoholic strength of the centrifuged wine from the previous day /100

The inclusion of the term "Juice in the distillery's clarifiers" in the above expression is not correct, but it does not significantly affect the results, being a day-to-day compensated estimate.

At the closing time of the survey of the process, it may happen that the fermenters are being fed with mash or are in process at the fermentation phase or in the centrifugation stage or are inactive. In practice, the measured volumes of all the vats and tanks are estimated and summed, and the result is multiplied by the mean volumetric ethanol strength ($\%_{v/v}$) of the centrifuged wine sampled at the exit of the centrifuges. This calculation assumes that all material, including distillery clarifiers juice, will have the same percentage of ethanol as the centrifuged wine sent for distillation. This approximation appears to be sufficiently close for the day-to-day compensated estimate.

Materials may be returned to the centrifuged wine tank, such as second-rate ethanol, and as water from ethanol recovery from the towers. The ethanol in the return tanks must be calculated using the known value of its volumetric ethanol content.

Estimation of the ethanol in-process in the yeast treatment tanks

Yeast treatment vats may sometimes be ignored in the calculation of in-process ethanol since it is a cyclic material. Its in-process calculation assumes that the ethanol content of yeast does not vary much from day to day:

Ethanol in-process in yeast treatment vats (L) = Yeast in treatment (L) * Average volumetric ethanol content of yeast treated in the previous 24 h ($\%_{v/v}$) / 100

Ethanol in-process expected in the molasses

At the daily closing, the volume of molasses in stock in the tanks must be measured and added to the virtual molasses in-process at the sugar factory, as was calculated previously.

Density of molasses in stock (kg/m^3) = 0.018223 * Molasses $Brix^2$ + 3.698409 * Molasses Brix + 998.2429

Molasses in stock (kg) = Volume of molasses stock (L) * Specific mass molasses stock (kg/m^3)/ 1000

Molasses in stock plus virtual molasses (kg) = Molasses in stock (kg) + Virtual molasses (kg)

The "virtual molasses in the sugar factory" was calculated in the previous item, on sugar in-process. The change (from the previous day) in the total molasses (stock in the tanks and virtual in the sugar factory) must be converted into its theoretical equivalent volume of ethanol, to be considered part of the day's ethanol production.

Considering three values of Distillery Overall Efficiency (DOE) and three values of total reducing sugars (TRS) % molasses, the theoretical yield of ethanol (L/t molasses) will be as in the following table showing ethanol yield variation with TRS % molasses and the DOE:

Efficiency	**TRS % molasses**		
TRS ->	50	55	60
DOE	L of ethanol/t of molasses		
80	259	285	311
84	272	299	326
88	285	313	342

Assuming a mean yield of 300 L of ethanol/t molasses, the estimate of theoretical ethanol in-process plus ethanol in virtual molasses can be simplified to:

Estimated of ethanol in stock and virtual molasses (L) = (Molasses in stock + Virtual molasses) ∗ 0.3

Any error caused by this approximate calculation will be compensated when the molasses is sent to the distillery. This approximation appears to be sufficiently close enough for the day-to-day compensated estimate

In-process total ethanol

The sum of the in-process ethanol in the three areas discussed above, i.e., the fermenters, yeast treatment tanks, and expected in the molasses, represents the value of the "Total volume of ethanol in process". It is noted that there is no high precision in the assessment of the ethanol volumetric content of the in-process material. The daily means of analytical determinations, brix, pol, and alcoholic strength are considered satisfactory indications of the result at the time of the survey.

For these reasons, and the fact that there are usually only small differences in tank volumes between subsequent days, it is considered that large investments and high additional costs to improve the quality of this information are not justified.

13.3 Example of an estimation of ethanol in-process

The following data shows a fictitious example of calculations involved in the estimation of in-process ethanol:

Molasses stock and equivalent ethanol

Molasses in storage tanks (at today's close)	340,000 kg
Virtual molasses in the sugar factory at today's close (see sugar in-process)	384,248 kg

Stock of molasses + Virtual molasses:

Today's total	724,248 kg
Yesterday's total	699,324 kg

Molasses stock variation = Today's total - Yesterday's total = 24,924 kg

Ethanol per kg of molasses (assumed) = **0.3** L/kg

Ethanol in-process

Ethanol in the distillery in-process (survey)	461,093 L
Ethanol in the distillery measuring tanks	0 L

The stock of molasses + virtual molasses = 724,248 kg

Ethanol molasses stock + virtual molasse = **0.3** $*$ 724,248 = 217,274 L

Ethanol distillery in-process at today's close = 461,093 + 0 + 217,274 = 678,367 L

Total ethanol in-process yesterday closing = 644,797 L

Ethanol in-process variation = 678,367 - 644,797 = **+33,570** L

14 Sugar and ethanol production control

For industrial control calculations, sugar yields must be expressed in kilograms (kg) and no decimal place. If they were recorded in bags of 50 kg or 46 kg (yard) or big bags of 1.0 to 1.2 t, enter this unit in the system (software) and convert it to kilograms to perform the calculations.

For presentation in bulletins and reports, the results can be converted into 50 kg bags or tons of sugar or another unit of measure usual in the company.

14.1 Sugar production

Sugar production is measured daily, and samples are periodically collected for analysis.

The production (kg) of each type of sugar must be multiplied by its corresponding pol to be converted into sugar and added together to obtain the "total production of sugar".

The use of fixed factors for sugar pol should be avoided, although the error may be negligible. The software in the control system should be checked to see if there is a corresponding pol specification for all the types of sugar produced. If there is no pol for some type of sugar, a default value of pol can be used.

Sugar reprocessing

In some situations, the reprocessing of sugar that had already been allocated as production may occur. As well, some mills may receive sugar from another sugar factories for reprocessing or refining. In these cases, a fixed loss of imported sugar must be considered to balance the extra sugar recovered in the reprocessing, and this estimated loss must be subtracted from the daily production since these sugars do not come from the plant-processed cane.

For each type of reprocessed sugar:

Reprocessed sugar 100% (kg) = Reprocessed sugar (kg) ∗ Sugar pol / 100 ∗ Reprocessed sugar Recovery efficiency / 100

The recovery efficiency of reprocessed sugar is set to an arbitrary value guided by its SJM recovery, as it is impracticable to find the exact recovery value.

Sugar production plus in-process variation

When estimating the sugar production in daily, allowance has to be made for any reprocessed sugar. With all values expressed as pure sugar or sucrose in kilograms:

Produced sugar = Actual sugar production + In-process sugar variation - Reprocessed sugar

This value will be applied in all yield, efficiencies, and TRS mass balance calculations.

Total sugar production in the 24 h period (informed)	798,480 kg
In-process sugar variation (+today -yesterday)	11,953 kg
Reprocessed sugar (informed)	0 kg

Produced sugar = 798.480 + 11.953 - 0 = 810,433 kg

The "Reprocessed sugar" in the equations above can include raw sugar received from third parties and returned sugar from clients.

14.2 The effect of input and output of molasses on the ethanol balance

In several plants, mainly belonging to the same economic group, it is an established practice to exchange molasses and other products, such as in the case of the yeast cream mentioned before.

For the ethanol balance, any molasses purchased (input) or sold (output) must be converted into the equivalent theoretical volume of ethanol. The result must be added to the ethanol production for output molasses or subtracted for input molasses.

It should be noted that the ethanol equivalent of the molasses in-process and "virtual" molasses has already been added to the "ethanol in-process", as outlined in the previous chapter.

Estimation of the ethanol equivalent in the input and output molasses

The theoretical ethanol estimate can be approximate for molasses in stock or in-process at the sugar factory (virtual molasses) since the probable error will be corrected when this material passes through the distillery. However, for the input and output of significant amounts of molasses from other factories, such errors will not be corrected or compensated for, and this requires a better estimate of the theoretical ethanol volumes involved in the input or output molasses.

Normally, all molasses input and output are weighed and a sample is taken from each load to determine brix and pol to calculate its apparent purity. The TRS % molasses content can be determined on each load or a composite sample per day.

Total TRS in molasses (kg) = Final molasses (kg) * TRS % molasses / 100

Ethanol in molasses (L) = Total TRS molasses (kg) * 0.6480 * Distillery Overall Efficiency / 100

Where the constant 0.6480 is the stoichiometric factor for conversion of TRS to ethanol.

When large input/output quantities are involved, it would be interesting to use a table or equation that provides the Distillery Overall Efficiency (DOE) as a function of the molasses apparent purity, as already proposed by Fermentec (*www.fermentec.com.br*). The Fermentec equation is a simple linear regression:

$$\text{Distillery Overall Efficiency} = 0.26 * \text{Molasses apparent purity} + 71.0$$

Naturally, factors other than purity influence molasses fermentation efficiency. Some of these are, the technology adopted, the general supervision of the process, the amount of non-fermentable reducing substances, and the presence of components toxic to yeast.

However, there is no way to quantify those factors, except in the case of the non-fermentable reducing substances. If these can be measured, their amount can be subtracted from the total TRS, to obtain the "total fermentable sugars" (TFS).

All values being expressed in ethanol volumes (L) at 20 °C:

$$\text{Ethanol production plus in-process variation} = \text{Ethanol production} + \text{In-process ethanol today} - \text{In-process ethanol yesterday} + \text{Theoretical ethanol in the output molasses} - \text{Theoretical ethanol in the input molasses} - \text{Ethanol in reprocessed molasses}$$

This will be the ethanol value to be applied in all yields, efficiencies, and the TRS mass balance calculations.

The dry yeasts produced can be converted into equivalent ethanol and added to the total ethanol produced. A similar procedure can be adopted for the entry and exit of yeast cream or any other intermediate product of the process.

Note again that "Process ethanol" includes all ethanol in-process at the distillery (clarifiers, vats, non-pumped metering tanks), theoretical ethanol in molasses in stock in the tanks, and any "virtual" molasses at the sugar factory, as calculated previously.

Output molasses

Example calculation of the ethanol equivalent in any output molasses:

Molasses output (reported)	212,000 kg
TRS % output molasses (determined)	51.50%
Apparent purity of the output molasses	50.0%

Distillery Overall Efficiency for sent molasses = 0.40 ∗ Purity output molasses + 62.0 = 82.0%

Theoretical ethanol volume in output molasses = Output molasses ∗ TRS % molasses / 100 ∗ 0.6480 ∗ Distillery Overall Efficiency of the output molasses / 100
= 212,000 ∗ 51.5 / 100 ∗ 0.6480 ∗ 82.0 / 100 = **58,014** L

Input molasses

Example calculation of the ethanol equivalent in any input molasses:

Received molasses (informed)	350,000 kg
TRS % received molasses (determined)	49.0%
Received molasses purity (calculated)	50.0%

Distillery Overall Efficiency for received molasses = 0.40 ∗ Received molasses purity + 62.00
= 0.40 ∗ 50.0 + 62.00 = 82.0%

This linear regression equation of "Distillery Overall Efficiency versus Molasses purity" was empirically and pragmatically deduced, using values suggested by Fermentec.

It can be replaced by the value of the DOE obtained by the company that receives the molasses.

Theoretical ethanol in input molasses = input molasses * TRS % received molasses / 100 * 0.6480 * DOE of input molasses / 100
= 350,000 * 49.0 / 100 * 0.6480 * **82.0** / 100 = **91,128** L

14.3 Dry yeast production equivalent to TRS

Normally, it is considered that to produce each kilogram of dry yeast, 2.0 kg of TRS is required. Thus, the multiplication of the total dry yeast produced (kg) multiplied by two (2) results in the TRS being added to the total TRS of the products (kg).

Input and output yeast cream equivalent as TRS

The yeast cream can be sent to another industrial unit to start or "boost" the fermentation or to produce dry yeast.

If the quantity is significant, the plant that provided the product may lose in the production of ethanol, both due to the dry matter produced by the multiplication of yeasts, and to the ethanol contained in the yeast cream. The latter may be ignored in the calculations, as its recovery is uncertain.

The dry matter contained in the yeast cream (kg) should be multiplied by two (2) and its TRS result added to the total TRS of the products (kg). For the plant receiving the yeast cream its TRS result should be subtracted from the TRS of its products.

Example calculation of TRS for a yeast cream output

Informed figures:

Yeast cream sold	15,000 kg
Yeast % yeast cream	60.00%

Ethanol % yeast cream	3.50%
Yeast drying efficiency	98.0%

Calculations:

Total TRS yeast sold = Yeast cream sold * Yeast % yeast cream / 100 * Yeast drying efficiency / 100
= 15,000 * 60.00 / 100 * 98.0 / 100 = 8,820 kg

Ethanol yeast cream sold = Yeast cream sold * Ethanol % yeast cream / 100 * 0.99 / 0.648
= 15,000 * 3.50 / 100 * 0.99 / 0.648 = 802 kg

Total ART yeast cream sold = Total ART yeast sold + Total ART ethanol yeast cream sold
= 8,820 + 802 = 9,622 kg

Ethanol in yeast sold = Total ART yeast cream sold * 0.648
= 9,622 * 0.648= 6,235 L

14.4 Ethanol production

All types of ethanol must have the volumes recorded in liters (L) and without decimals.

The volumes of ethanol produced must be reported at 20 °C, according to the volume correction as a function of the ethanol temperature determined in the tank at the time of measurement and the corresponding ethanol content ($\%_{m/m}$). In Brazil, using ABNT standards established by INMETRO is mandatory following the methodology described by Bettin & Spieweck (1990) and recommended by OIML.

Ethanol strength by volume $\%_{v/v}$
(L ethanol / 100 L of the hydroalcoholic mixture at 20 °C)

Ethanol strength by mass $\%_{m/m}$
(kg of ethanol / 100 kg of the hydroalcoholic mixture at 20 °C)

Conversion of various alcoholic grades to ethanol

The diverse types or grades of alcohols produced, including second-grade alcohols, must be converted to 100% grade (absolute ethanol or ethanol) to be recorded as "ethanol". The records are as volumes (L) so it is necessary to calculate the volume of ethanol produced with an ethanol strength by volume of $100\%_{m/m}$ for a given type of ethanol. Sometimes, though, the values are on a $100\%_{m/m}$ basis.

The following equations are applied:

Ethanol 100% produced (L) = Ethanol volume at 20 °C * Alcoholic strength by volume / 100

Or:

Ethanol 100% produced (t) = Ethanol volume at 20 °C * Alcoholic strength by mass * Density of ethanol produced / (100 * 789.23)

In Brazil, the density of ethyl ethanol (kg/m^3) is obtained from the ABNT system. The density of absolute ethanol (100% at 20 °C) equals 789.23 kg/m^3 (Bettin & Spieweck equation 1990).

Note the density of common grades of ethanol (at 20 °C):

a) For **hydrous** alcoholic strength by mass (HASm) in the range between $92.0\%_{m/m}$ to $94.0\%_{m/m}$

Hydrous Ethanol Density = $-0.01891510122 * HASm^2 + 0.7544833955 * HASm + 903.175526$

b) For **anhydrous** alcoholic strength by mass (AASm) in the range between $98.3\%_{m/m}$ to $99.9\%_{m/m}$

Anhydrous Ethanol Density = $-0.03678494634 * AASm^2 + 4.212761107 * AASm + 735.808611$

c) Conversion:

Alcoholic strength by volume ($\%_{v/v}$) = Alcoholic strength by mass ∗ Density / (100 ∗ 789.23)

The total ethanol production will be obtained by summing the volumes corresponding to each type of ethyl ethanol expressed as liters of ethanol.

Calculations involved with ethanol reprocessing

When ethanol is reprocessed or returned to the storage tanks, the volume received to be reprocessed must be deducted from the production on the day, so that it is not included in the production of ethanol originating from the processed cane.

Due to the circumstances of each sugar/ethanol factory, the ethanol reprocessing calculations may vary between factories. Ethanol received from return or third parties must also be converted to equivalent ethanol 100% (density 789.23 kg/m^3 at 20 °C) as for reprocessed ethanol.

For each type of reprocessed ethanol (L):

Reprocessed ethanol = Reprocessed ethanol at 20 °C ∗ Alcoholic strength by mass of reprocessed ethanol ∗ Density of ethanol / (100 ∗ 789.23)

Reprocessed ethanol = Returned ethanol ∗ Alcoholic strength by mass of reprocessed ethanol ∗ Density of ethanol / (100 ∗ 789.23)

Recovered volume of ethanol = Reprocessed ethanol ∗ Reprocessed ethanol recovery efficiency /100

The fixed loss for "Reprocessed ethanol recovery efficiency" must be set at an arbitrary value, as it is not practicable to determine an exact coefficient. A value of about 95% might be typical for recovery efficiency from uncontaminated ethanol mixtures being reprocessed.

Example of ethanol production calculation

As nominated before:

Produced ethanol	685,240 L
In-process ethanol variation (+today -yesterday)	33,572 L
Ethanol reprocessed and recovered (informed)	25,000 L
Theoretical ethanol in the output molasses	58,014 L
Theoretical ethanol in the received molasses	91,128 L
Yeast ethanol exported	6,235 L

Calculations:

Variation in "ethanol molasses" and "yeast products" = Theoretical ethanol output molasses - Theoretical ethanol input molasses + Yeast ethanol exported
= 58,014 - 91,128 + 6 235 = -26 879 L

Ethanol 100% produced = Produced ethanol + In-process ethanol variation - Reprocessed ethanol + Variation ethanol molasses and yeast
= 685,240 + 33,572 - 25,000 - 26,879 = **666,933 L**

14.5 Molasses production

Most sugar factories in Brazil use two-boiling systems since it is not necessary to fully exhaust the molasses as its excess sugar content simply replaces other sugar in the distillery feedstock. The molasses typically has an apparent purity between 50% and 60% and is considered an intermediate product since this molasses will be used as feedstock for fermentation

For Brazilian plants that work with a two-mass boiling system, B-molasses produced is not regularly measured, since it is all sent to the distillery to produce ethanol.

If necessary, molasses mass flows or molasses yields can be obtained by weighing on batch scales, by mass flow meters, and by measuring changes in storage tank depths using mercury column pressure readings.

When measuring "molasses consumed", the mass of molasses produced in the 24 h period can be estimated by:

Produced molasses plus process variation = Consumed molasses + Output molasses - Input molasses + Molasses in stock plus "virtual' molasses today - Molasses in stock plus "virtual" molasses yesterday

In Brazil, the in-process materials will produce sugar and molasses, the quantity of molasses being calculated by using the SJM formula, and it is called "virtual molasses". All mass values are expressed in kilogram units.

The following calculation can be used when there are lesser amounts of input and/or output molasses with approximately the same brix and/or TRS % molasses as the in-house virtual molasses.

For greater precision in the calculations, the production estimate must consider the determined TRS % molasses for any input and output transfers during the survey period:

Total TRS in molasses produced plus in-process variation = Total TRS in molasses consumed + Total TRS in molasses output - Total TRS in molasses input + Total TRS in stock and virtual molasses today - Total TRS in stock molasses and virtual yesterday

Total molasses produced plus in-process variation = 100 * Total TRS in molasses produced plus in-process variation / TRS % molasses

When TRS % molasses is not available for each type of molasses, the above calculation can be performed considering the brix of each type of molasses instead of its TRS %.

Generally, molasses production is expressed as @ 85% brix (or @ 82% brix), to standardize the results. To do so, multiply the production in kg of brix in molasses by 100 and divide the result by its brix (85% or 82%). The molasses yield can be expressed in kg per ton of cane, kg per t sugar produced, or as a percentage of cane.

In South Africa, for example, considering the mean for 14 mills in 17 harvesting seasons (2001 to 2017), the production of fully exhausted final molasses is 41.82 kg/t cane (**Table 14.1**). Final molasses from Australian mills have a lower RS/Ash ratio and a larger difference between their true purity and apparent purity values.

Table 14.1 – Final molasses results obtained by 14 mills in 17 harvesting seasons (2001 to 2017) in South Africa.

Results	Mean	Minimum	Maximum
Refractometer brix	84.1	83.0	85.1
Apparent purity	35.5	33.9	36.9
True purity	38.1	36.7	39.8
Conductivity ash	14.1	13.0	15.0
Fructose	7.08	5.83	7.58
Glucose	4.96	4.38	5.47
(Glucose + fructose) / ash	0.85	0.74	0.91
Molasses @ 85% brix (kg/t)	41.82	37.3	47.0
Pol/sucrose ratio in molasses	0.93	0.92	0.94

15 Factory yield and efficiency

"Yield" or productivity is the amount of product per unit of raw material, such as, for example, sugar yield (kg/t cane), and ethanol yield (L/t cane), which depend on several factors like the quality of the raw material and the process performance, fermentation yield (L ethanol produced per kg of ATR in the mash), bagasse yield (kg/t cane).

"Efficiency" expresses how much product was recovered about the total available, that is, it is a percentage value. Fermentation efficiency (ethanol produced % available ethanol in the mash) is an example.

15.1 Sugar yield per ton of cane

For mills that exclusively produce sugar with exhausted low-purity molasses, simply dividing the total sugar production by the total processed cane will result in the sugar factory yield, presented in kg of sugar/ton cane or as a percentage (used in several countries).

In South African mills, this measure also appears as "tons of cane/tons of sugar" with a weighted mean for 14 mills in 17 harvesting seasons (2001 to 2017) of 8.66 t cane/t sugar, which corresponds to 115.1 kg of sugar/t cane, varying between harvest means from 105 to 120 kg/t cane.

Before the beginning of the National Ethanol Program in Brazil (Pro-Álcool) in November 1975, the mean industrial yield of Brazilian mills was 94 kg sugar/t cane in the Center-South region (São Paulo state), and 90 kg/t cane in the Northeast region (Alagoas and Pernambuco states).

In São Paulo, during that time, pol % cane was around 12.5% in the mean harvest of all mills, which resulted in an "overall recovery" (O.R.) of only 75.2% ($10 * 94 / 12.5$).

15.2 Effective yield of sugar and ethanol in sugar/ethanol factories

To obtain an overall yield in sugar/ethanol factories in the 24 hours it is necessary to sum the outputs of sugar to ethanol, including their respective in-process variations. To do this it is convenient that all outputs are stoichiometrically converted into "total reducing sugars" (TRS).

Example calculation of the total of TRS in sugar and ethanol

TRS in sugar and in-process variation = Produced sugar (kg) / 0.95
= 810,433 / 0.95 = 853,087 kg

TRS in ethanol and in-process variation = Ethanol 100% produced (L) / 0.6480
= 666,933 / 0.6480 = 1,029,218 kg

TRS in sugar and ethanol = TRS in sugar + TRS in ethanol
= 853,087 + 1,029,218 = 1,882,305 kg

Effective sugar yield = Sugar produced (kg) / Milled cane (t)
= 810,433 / 13,398.324 = 60.49 kg/t cane

Effective ethanol yield = Ethanol 100% produced (L) / Milled cane (t)
= 666,933 / 13 398.324 = 49.78 L/t cane

TRS yield = TRS in sugar and ethanol (kg)/ Milled cane (t)
= 1,882,305 / 13,398.324 = 140.49 kg/t cane

Of course, these effective yields depend on the production mix and therefore cannot be considered as performance value.

TRS in the product % total TRS produced

TRS in sugar % total TRS produced = 100 ∗ TRS in sugar / TRS in sugar and ethanol
= 100 ∗ 853,087 / 1,872,680 = 45.32%

TRS in ethanol % total TRS produced = 100 ∗ TRS in ethanol / TRS in sugar and ethanol
= 100 ∗ 1,029,218 / 1,882,305 =. 54.68%

15.3 Example calculation of Total Recovery

The Total Recovery indicates the percentage of Total Reducing Sugars (TRS) in cane that was recovered by the factory in sugar and ethanol as TRS. In Brazil, this concept is referred to as "general industrial efficiency" (EGI).

Total Recovery = 100 ∗ TRS in sugar and ethanol / Total TRS in milled cane
= 100 ∗ 1,882,305 / 2,112,916 = **89.09%**

Interpretation of Total Recovery of TRS

"Total TRS Recovery" is the main indicator of the performance of the sugar and ethanol factory process. The recovery result depends on numerous variables, such as:

a) the start and end dates of milling,
b) the equipment available,
c) the state of maintenance and the operational efficiency of the plant unit,
d) the production mix (calculated in the previous item),
e) the quality of the raw material (mainly pol % cane and juice purity),
f) the individual section efficiencies (mainly the fermentation efficiency), and

g) the undetermined losses of sugars.

Depending on these factors, the mean accumulated Total TRS Recovery of the crop in Brazil can be between 88% and 92% for a production mix with sugar between 50% and 60% of the TRS production.

When the production is sugar with fully exhausted molasses, and there is no distillery plant attached, the Total Recovery can exceed 92% in highly efficient plants. For the exclusive production of ethanol (autonomous distillery), this efficiency indicator remains between 81% and 86%.

According to data from UNICA[1] and Consecana-SP[2], the Total Recovery in Brazil fluctuated between 84.0% and 86.5% in the 2006 to 2015 harvesting seasons (**Figure 15.1**).

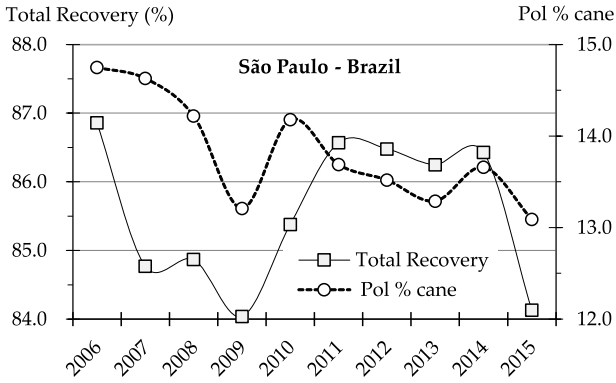

Figure 15.1 – Average results of pol % cane (Source: Consecana-SP) and Total Recovery of TRS calculated with data available on www.unicadata.com.br (03/Jan/2020).

Although the data used come from two different sources for the same population (UNICA and Consecana-SP), the Total Recovery results in

[1] *www.unicadata.com.br*
[2] *www.consecana.com.br*

São Paulo (2006 to 2015) were well below the expected from 88% to 92% cited above.

The Total Recovery in South African mills is called Overall Recovery (O.R.) and it is calculated by dividing the total sucrose (pol) in sugar produced by total sucrose (pol) in processed cane. The arithmetic mean of the O.R. in South African mills in the 2001 to 2017 harvests was 84.9%, ranging from 81.0 to 87.3% and a mean of 84.9 $\pm$0.9.

Of course, the O.R. of the sugar mills in South Africa cannot be compared with the Total Recovery of the Brazilian plants, as they deal with different conditions to produce sugar and ethanol or molasses.

16 Distillery control

Controls in the distillery sector aim to ensure that the highest possible efficiency is achieved in the fermentation and distillation processes. Therefore, accurate sampling and analytical methods and rigorous microbiological control are necessary.

16.1 Analysis of the mash

The mash is an intermediate material in the industrial process that requires strict analytical and microbiological control, especially for plants that use a large part of the cane juice and intermediate molasses from two massecuites to produce ethanol, as is the case in Brazilian sugar and ethanol mills.

Alcoholic strength by volume at 20.0 °C (%v/v) and yeast concentration are the two essential analytical determinations for treated yeast cream, raw wine, centrifuged wine, and the centrifuged wine in the vat waiting for ethanol distillation. Other complementary analytical determinations are pH, sulfuric acidity (fixed), and glycerol.

When working with **batch fermentation**, sampling for the analysis should preferably be conducted "vat by vat".

For **continuous fermentation**, the raw wine and the treated yeast in the treatment vats must be manually sampled every four hours or at the same frequency by a continuous sampling system

Sampling and analysis of the mash

The mash is sampled continuously in the feed line to the fermenters, either before the heat exchanger cooling system or after the cooling exchanger. Both arrangements require an asepsis system to avoid contamination of the sample.

A continuous rod-type mass sampler or solenoid valve can be used, and the sample is preserved in a special compact refrigerator installed at the sampling site. The sample is kept refrigerated in a range of temperatures between 2 °C to 8 °C. It should be noted that mercuric chloride or bichloride (also called corrosive sublimate, a chemical compound, and white crystalline solid laboratory agent with the formula $HgCl_{2,}$), should not be used as a preservative due to its high toxicity.

Analytical determinations for samples of the mash

The mash must be analyzed every four hours. Determinations of brix % mash and TRS % mash are essential, as they are used in the calculations of the "fermentation efficiency" and of the TRS mass balance.

A variation of 0.5 mL in the volume spent in the titration using the method of Lane & Eynon (1923) in the determination of TRS represents a difference of a single percentage point in the subsequent calculations of fermentation efficiency. Fortunately, as these titration errors are mostly random, they are compensated for in the calculation of the arithmetic mean of the 24-hour periods and over the entire season.

Other determinations allow improved monitoring of the mash. These can include analysis of the pol % mash (to enable calculations of the purity of the mash), the insoluble (by centrifugation or gravimetry), the sulfuric acidity, the pH, and the reducing sugars. Other special analyses may be for sulfite, dextran, starch, phosphorus, potassium, calcium, magnesium, aluminum, and nitrogen, as well as rigorous microbiological monitoring. The decision to put any of these determinations into the routine of the lab is an individual decision of each company.

Having results for the pol % mash and brix % mash, it is possible to calculate the mash purity. Purity will be lower for the greater the proportion of final molasses and the lower purity would depress the fermentation efficiency. With results for TRS % mash and reducing sugars % mash, the sucrose % mash can be estimated.

Example data for mash calculations:

Brix % mash	22.5%
Mash saccharimeter reading (200mm tube)	71.15 °Z

Density, pol, and purity calculations

Mash density regression equation:

Mash density (estimated by regression) = $0.015726 * \text{Brix \% mash}^2 + 3.81451 * \text{Brix \% mash} + 997.362$
$= 0.015726 * 22.5^2 + 3.81451 * 22.5 + 997.362 = 1091.150$ kg/m

Mash density (ICUMSA Table) = 1091.144 kg/m^3

Pol % mash = Saccharimeter reading $*$ (0.26065 - 0.000995 $*$ Brix % mash)
$= 71.15 * (0.26065 - 0.000995 * 22.5) = 16.95\%$

Mash purity = 100 $*$ Pol % mash/ Brix % mash
$= 100 * 16.95 / 22.5 = 75.3\%$

Reducing sugars % mash by Lane & Eynon

For reducing sugars determination, mash dilution must be performed using volumetric pipettes and 200 mL flasks. Using 200 mL flasks and commercially available pipettes, the following dilutions can be obtained:

Mash* ml	EDTA ml	Dilution relation	Dilution factor
20	2	1:10	10
40	4	1:5	5
50	5	1:4	4
100	10	1:2	2
200	20	1:1	1

* *Volume of mash in the 200 mL volumetric flask, to enable repetitions of the titration.*

After diluting the mash sample, titrate 10 mL of Fehling's liquor. If the volume spent in the titration is outside the range of 15 to 50 mL, the dilution must be changed. If the volume is below 15 mL, it will be necessary to use a higher dilution. Otherwise, when the volume exceeds 50 mL, the dilution should be reduced.

Example of reducing sugars % mash calculations

Fehling's Liquor Correction Factor	0.9946
Mash dilution for titration	4
Volume spent on titration	28.6 mL

Corrected volume = Volume spent ∗ Correction Factor
= 28.6 ∗ 0.9946 = 28.45 m

Reducing sugars % mash = Mash dilution ∗ (5.2096 - 0.2625 ∗ ((0.26 ∗ LS/ Mash dilution)$^{1/3}$)) / (Corrected volume ∗ (0.00431 ∗ Brix % mash + 0.99367))
= 4 ∗ (5.2096 - 0.2625 ∗ ((0.26 ∗ 71.15/ 4)$^{1/3}$)) / (28.45 ∗ (0.00431 ∗ 22.5 + 0.99367)) = 0.62%

This equation (Fernandes, 1984a) gives the same results for reducing sugars as the Lane & Eynon (1922) original table, avoiding the work of interpolations between columns and lines.

Determination TRS % mash

Informed example values for TRS analyses:

Fehling's Liquor Correction Factor	0.9946
The initial mass of the mash	25.32 g
The volume of the first volumetric flask	200 mL
The volume of the first dilution	20 mL
The volume of the second volumetric flask	200 mL
Volume spent on titration TR	24.1 mL

Calculations of TRS % mash

Corrected volume = Volume spent on titration ∗ Correction Factor
= 24.1 ∗ 0.9946 = 23.97 mL

Mass of mash TRS = 1000 ∗ Initial mass ∗ Volume of the first dilution / (Volume of the first flask ∗ Volume of the second flask)
= 1000 ∗ 25.32 ∗ 20 / (200 ∗ 200) = 12.6600 g/L

TRS % mash = 10 ∗ (496.4404 / Corrected volume + 0.605) / Mass of mash TRS
= 10 ∗ (496.4404 / 23.97 + 0.605) / 12.6600 = **16.84**%

This equation above, deduced by Fernandes (1984a), gives the same results for total reducing sugars (TRS) as the Lane (1923) original table, avoiding the work of interpolations between columns and lines.

Sucrose % mash

Sucrose % mash = (TRS % mash - Reducing sugars % mash) ∗ 0.95
= (16.84 - 0.62) ∗ 0.95 = 15.41%

Example calculation of TRS % brix in mash

TRS % brix in mash = 100 ∗ TRS % mash / Brix % mash
= 100 ∗16.84 / 22.5 = 74.8%

Note: The "*TRS % mash = Pol % mash /0.95 + Reducing sugars % mash*" estimate should not be used, especially when composed of B-molasses or final molasses thus giving a purity of mash that is less than 82%.

16.2 The traditional batch fermentation

The Melle-Boinot fermentation process is simple and most traditionally used in distilleries. The calculation methodology presented below can only be applied in systems with batch or intermittent fermentation without flow meters. It consists of measuring the volume of yeast

added to the vat (vat footing) and the total volume of wine in the vat at the end of feeding with the mash (**Figure 16.1**). The mash volume is obtained by difference. As it is a measurement performed on a routine scale, it can result in values very far from the real if care is not taken with the measurement of volumes and in the analytical determinations of TRS.

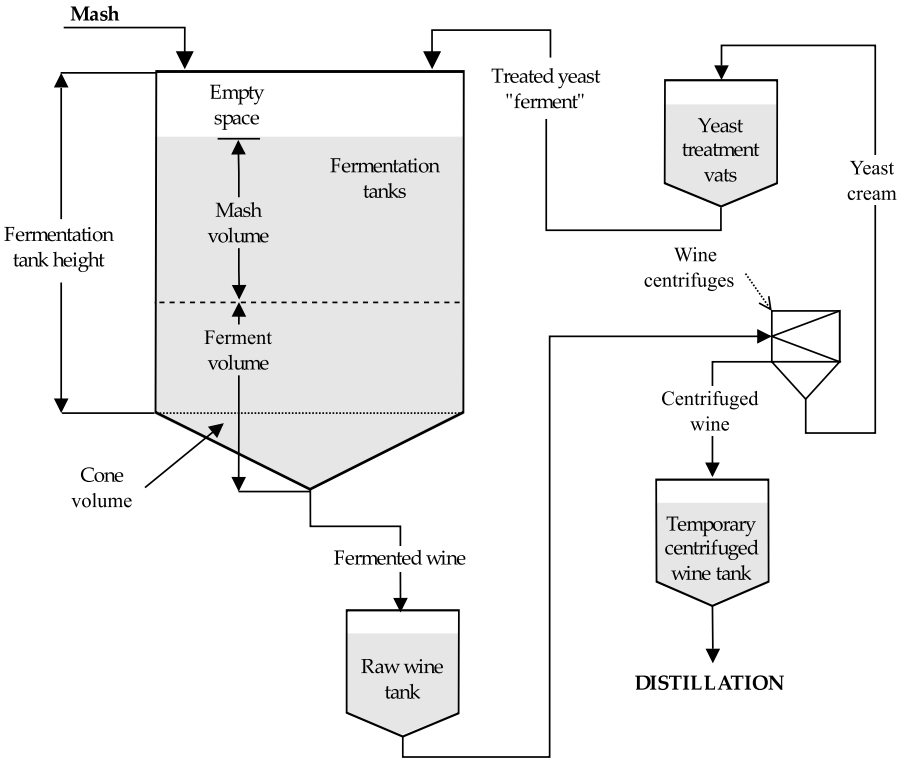

Figure 16.1 – Diagram of determination of the volumes of mash, treated yeast cream (ferment), and raw wine to calculate the efficiency of discontinuous or batch fermentation.

The total volumes of raw wine from all fermenters centrifuged in the day or period, as well as all yeast treatment vats (vat foot), must be summed. This calculation can be performed "fermenter by fermenter"

and the results in mass and volumes are summed at the end of the day or period and added to the accumulated results for the harvest season.

Example of informed data for batch fermentation

Raw wine = 8,592,400 L (total volume of finished fermenters informed)

Yeast = 2,320,000 L (total volume of yeast in the treatment vats informed)

The "raw wine" is the material in the fermenter tank after finishing the fermentation process and before the centrifugation to separate the wine from the yeast. "Yeast cream" is the "ferment" after treatment of the yeast that is returned to the fermentation tank for a new cycle.

Daily or period mean (calculated in the previous item):

Brix % mash	22.5%
TRS % mash	16.84%
Alcoholic strength by volume of raw wine	$8.70\%_{v/v}$
Alcoholic strength by volume treated yeast cream	$3.60\%_{v/v}$

Example of calculations for batch fermentation

Ferment % raw wine = 100 * Yeast cream volume / Raw wine volume

= 100 * 2,320,000 / 8,592,400 = 27.00%

Density of the mash (ICUMSA) = 0.015726 * Brix % mash^2 + 3.81451 * Brix % mash + 997.36

= 0.015726 * 22.5^2 + 3.81451 * 22.5 + 997.36 = 1091.148 kg/m^3

Volume of mash = Raw wine volume - Yeast cream volume

= 8,592,400 – 2,320,000 = 6,272,400 L

Mass of mash = Volume of mash * Density of the mash / 1000
= 6,272,400 * 1091.148/ 1000 = 6,844,117 kg

Total of TRS in the mash = Mass of mash * TRS % mash/100
= 6,844,117 * 16.84/ 100 = 1,152,549 kg

Theoretical ethanol in the mash = Total TRS in the mash * **0.6480**
= 1,152,549 * 0.6480 = 746,852 L

Note: The coefficient **0.6480** was explained in the "Stoichiometry" Chapter 5.3, seen earlier.

Ethanol in raw wine = Volume raw wine * Alcoholic strength by volume of raw wine / 100
= 8,592,400 * 8.70 / 100 = 747,539 L

Ethanol in the ferment = Yeast cream volume * Alcoholic strength by volume of treated yeast cream / 100
= 2,320,000 * 3.60 / 100 = 83,520 L

Ethanol produced in the fermentation = Volume of ethanol in the raw wine - Volume of ethanol in the ferment
= 747,539 – 83,520 = 664,019 L

Ethanol lost in fermentation was calculated considering the volumes of fermenters and yeast cream treatment tanks. Only vats containing fully centrifuged finished ferment are considered in this calculation.

Ethanol lost in the batch fermentation = Theoretical ethanol in the mash - Ethanol produced in the fermentation
= 746,852 – 664,019 = 82,833 L

TRS not recovered in the batch fermentation = Ethanol lost in the batch fermentation / 0.6480
= 82,833/ 0.6480 = 127,829 kg

Yield of the batch fermentation

The yield of fermentation is presented as "Liters of ethanol per kilogram of TRS" in the mash, being the maximum stoichiometric yield equal to 0.6480 L/kg.

Yield of the batch fermentation = Ethanol produced in the fermentation / Total of TRS in the mash
= 664,019 / 1,152,549 = 0.5761 L/kg

Efficiency of the batch fermentation

Batch Fermentation Efficiency = Ethanol produced in the fermentation / Theoretical ethanol in the mash
= 664,019 / 746,852 = **88.91%**

The mean accumulated in the season must be calculated by the sum of "ethanol produced in fermentation" and "theoretical ethanol in the mash".

16.3 The continuous fermentation process

The technology of continuous fermentation is mostly conducted with three to five fermenter vats connected in series, using a system for yeast cell recycling (**Figure 16.2**).

Distillery informed data

Alcoholic strength by volume centrifuged wine	$8.55\%_{v/v}$
Alcoholic strength by volume treated yeast	$3.60\%_{v/v}$
Flegmasse per liter of ethanol (1.8 to 2.2 L/L)	2.0 L/L
Alcoholic strength of vinasse	$0.080\%_{v/v}$
Alcoholic strength of flegmasse	$0.012\%_{v/v}$

To control continuous fermentation, flow meters must be used to obtain the total volume of the mash for the day or period.

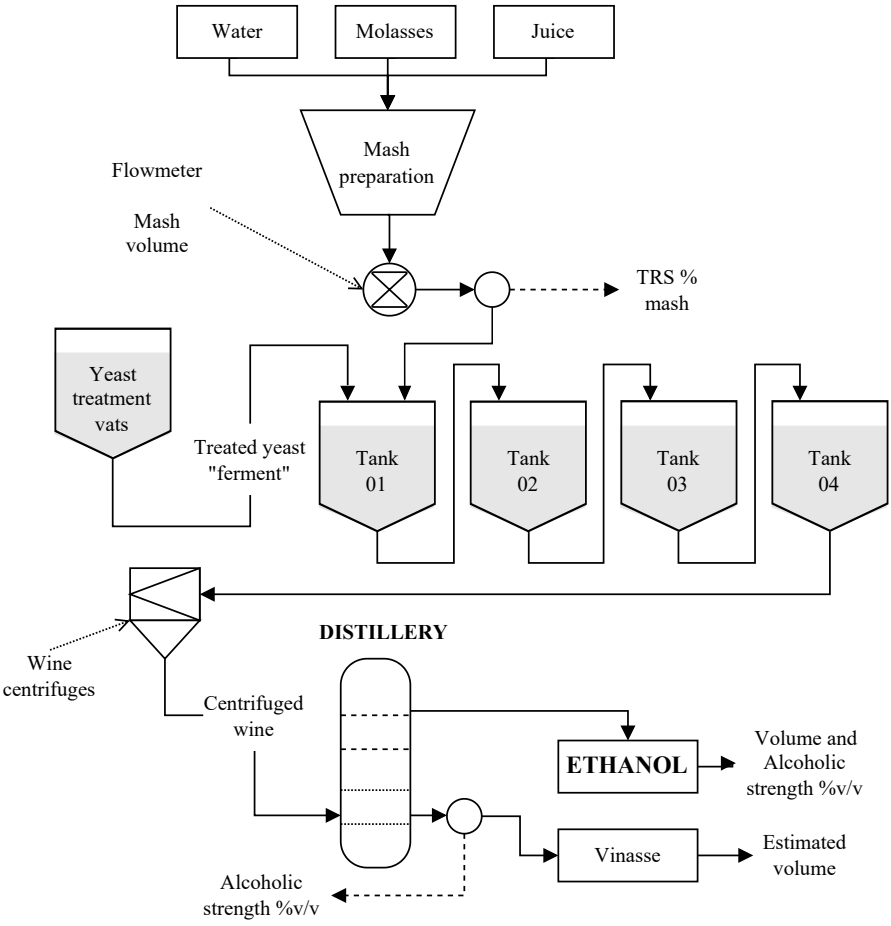

Figure 16.2 – A typical scheme for continuous fermentation.

Volume of mash (flow meters) 6,250,000 L
Brix TRS Density of the mash (ICUMSA) 1091.148 kg/m^3

Mass of mash = Volume of mash * Density of the mash / 1000
= 6,250,000 * 1091.148 / 1000 = 6,819,675 kg

Total of TRS in the mash = Mass of mash * TRS % mash / 100
= 6,819,675 * 16.84 / 100 = 1,148,433 kg

Theoretical ethanol in the mash (flow meter) = Total TRS in the mash * 0.6480
= 1,148,433 * 0.6480 = 744,185 L

Efficiency of the continuous fermentation

To obtain the volume of "ethanol produced in fermentation", it would be necessary to know the volume of raw wine sent to the centrifuges and the respective ethanol content. However, it is not recommended to measure the volume of raw wine with a flowmeter, due to the presence of gases and yeast cells.

For practical purposes, it can be considered that the "Ethanol in the raw wine" is equal to the "Ethanol produced" (see Chapter 14.4 "Ethanol production" = 666,933 L) plus the "Ethanol lost in the distillation process", that is, in vinasse and flegmasse (see Chapter 16.4).

In this proposal, only the ethanol lost in vinasse and flegmasse, are being considered. Other losses in the distillery will be part of the "undetermined losses".

Ethanol in the raw wine = Ethanol produced + Ethanol lost in distillation
= 666,933 + 5,869 = 672,802 L

Continuous Fermentation Efficiency = 100 * Ethanol in the raw wine / Theoretical ethanol in the mash
= 100 * 672,802 / 744,185 = **90.41%**

Recommendations for fermentation control

- Fermentation efficiency can be considered efficient when it is above 88% for molasses mash mixed with secondary juice, depending on the proportions and purity of these raw materials.
- For fermentation of mixed juice with purity above 85%, an efficiency of 90% to 93% would be expected.
- The calculation of fermentation efficiency by the mass balance of all by-products should only be applied when it is not possible to use the calculation methods described above.
- Inaccuracies in the calculated fermentation efficiency are mostly related to the sampling and analysis of the TRS % mash.
- The determination of the alcoholic strengths of the raw wine and the treated yeast also are a source of error in the estimation of fermentation efficiency.
- The volumes of fermenter vats and yeast vats must be rigorously evaluated in batch fermentation, and the accuracy and reliability of the mash flowmeter data in continuous fermentation must be routinely checked.
- Good control of the timing and quantity measurement of any inputs is helpful.

16.4 Distillation control

After the fermented mash, the raw wine goes through centrifuges to separate the yeast and the centrifuged wine (**Figure 16.3**). This wine is then sent to column A at the distillery, where the phlegm (with an alcoholic strength between 45 and 50%$_{m/m}$) and the vinasse are separated. The phlegm is sent to column B, resulting in hydrated ethanol (minimum alcoholic strength by mass of 93%$_{m/m}$) and flegmasse. The vinasse can be used as fertilizer or for fertigation in the crop, while

the flegmasse can be returned to the process or used in various other ways. The hydrated ethanol undergoes dehydration using dehydrating agents or molecular sieves, producing anhydrous ethanol (minimum alcoholic strength of 99.3%$_{m/m}$).

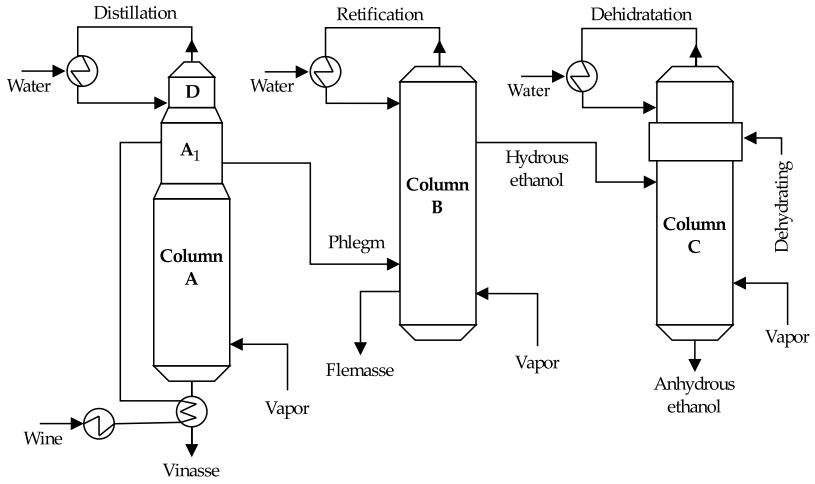

Figure 16.3 – Simplified diagram of ethanol distillation.

Technical control of distillation involves monitoring the volume, and alcoholic strength of the ethanol produced as well as the sampling, and analysis of the vinasse (stillage). These measurements are accompanied by direct pressure, temperature, and flow measurements around the distillation columns.

Monitoring the ethanol production

The ethanol produced can be sampled at 4 h intervals in the metering tanks and/or in the storage tanks or, in continuous production, continuously in the ethanol pipeline through the flow meters.

The frequency of sampling and analysis should be in every completed gauge tank just before it is pumped out into storage tanks. Sampling

and analysis must be performed daily in all storage tanks where ethanol has been moved, filled, or left stored.

The alcoholic strength by mass at 20.0 °C ($\%_{m/m}$), the ethanol temperature at the time of its volume measurement, the conductivity, the pH, and acetic acid content must be determined in the ethanol produced and sampled in all the measuring tanks and the storage tanks.

Example calculation of the distillation results

Measuring the volume of vinasse is not technically feasible due to the high volume produced daily and because it is acceptable to estimate this result based on the alcoholic strength of the centrifuged wine.

Vinasse per liter of ethanol = (100 - Alcoholic strength centrifuged wine) / Alcoholic strength centrifuged wine
= (100 - 8.55) / 8.55 = 10.70 L/L

Volume of vinasse = Vinasse (L/L) ∗ Produced ethanol / 1000
= 10.70 ∗ 666,933 / 1000 = 7,136.183 m^3

Due to the impossibility of directly measuring the volume of flegmasse, it is considered that each cubic meter of "ethanol produced" results in 2.0 liters of flegmasse.

Volume of flegmasse = Flegmasse per liter of ethanol ∗ Produced ethanol / 1000
= **2.0** ∗ 666,933 / 1000 = 1,333.866 m^3

The volume of "produced ethanol", see Chapter 14.4, includes **in-process variation**, considering theoretical ethanol due to molasses input and output, stocks of molasses, and reprocessed ethanol.

Ethanol loss in vinasse = 10 ∗ Volume of vinasse ∗ Alcoholic strength of vinasse
= 10 ∗ 7,136.183 ∗ 0.080 = 5,709 L

Ethanol loss in flegmasse = 10 ∗ Volume of flegmasse ∗ Alcoholic strength of flegmasse
= 10 ∗ 1,333.866 ∗ 0.012 = 160 L

Ethanol loss in distillation = Ethanol loss in vinasse + Ethanol loss in flegmasse
= 5,709 + 160 = 5,869 L

Ethanol produced plus loss in vinasse and flegmasse = Produced ethanol + Ethanol loss in distillation
= 666,933 + 5,869 = 672,802 L

Distillation efficiency

Distillation efficiency = 100 ∗ Ethanol produced / (Ethanol produced plus loss in distillation)
= 100 ∗ 666,933 / 672,802 = **99.13%**

We can note once more that "Ethanol produced and variation in the process" (660 696 L) includes all ethanol produced converted to 100%, plus the variation of ethanol in-process, juice decanters for ethanol, theoretical ethanol in molasses in stock, as well as theoretical ethanol due to molasses input and/or output to other industrial units, and inputs/outputs of other products containing ethanol.

Interpretation: For the distillation process conducted with good equipment and good control, its "Distillation Efficiency" is expected to be around 99.5 $\pm$ 0.2%.

16.5 Total losses of TRS in fermentation

Several technical publications describe in detail the stages of the Melle-Boinot process of alcoholic fermentation (**Figure 16.4**), including average data from Brazilian plants. Examples of these are Basso et al. (2011), and Andrietta et al. (2011).

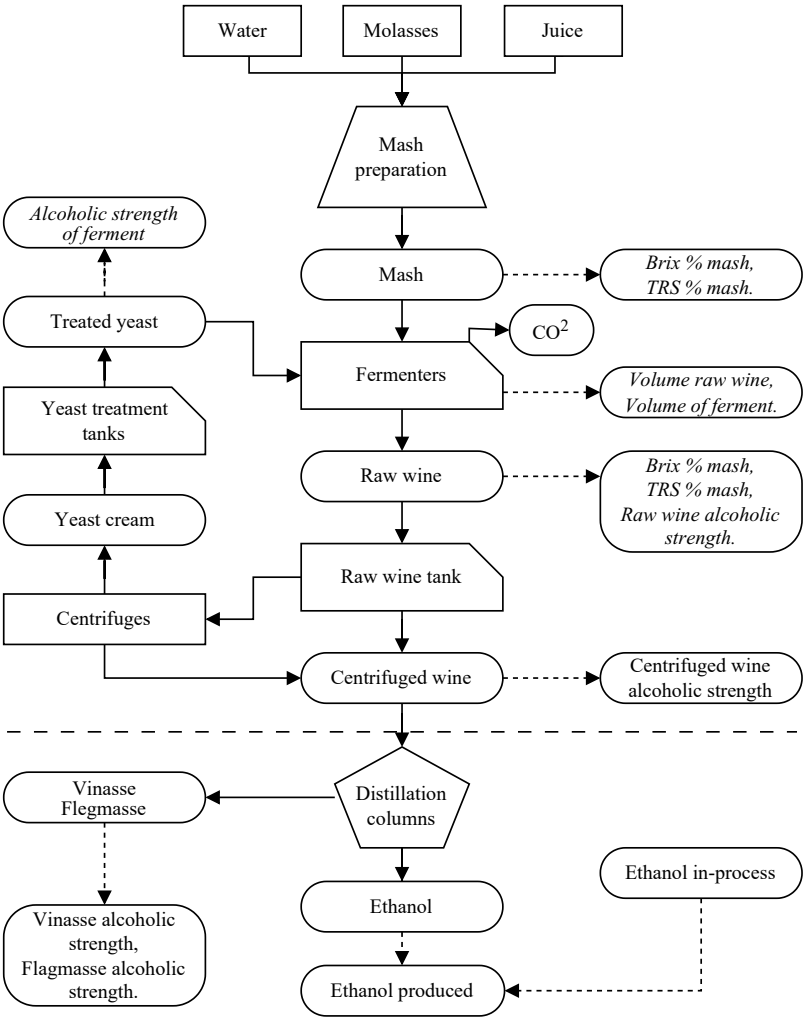

Figure 16.4 – Block flow diagram of the process used to produce ethanol from cane through fermentation and distillation.

The TRS lost in batch fermentation, with knowledge of the volumes of materials in all the fermentation vats and storage tanks, could be calculated by the difference between the total TRS in the mash and the TRS equivalent of the ethanol produced in the fermentation. In the example this loss was calculated before at 127,829 kg, considering only those fermenter vats with finished fermentation which had been fully centrifuged.

However, it may happen that some fermenters that were centrifuged were omitted from the control system. There is no way to detect any such failures other than by reviewing all the distillery notes. Because of this possible error, the "total losses of the fermentation" in all fermentation vats should not be considered.

Another drawback of this method is that it does not consider ethanol variations in the products in-process, in the molasses stock, and in the "virtual" molasses of the sugar factory. It could be argued: "But these in-process products have not yet been processed and therefore there are no losses to consider". However, it is a fact that, when the "daily or period closure" is carried out, the milling/distilling process is finalized, and was all the in-process material in the process.

An alternative is to perform the loss of TRS calculation "backward". AS shown the example and the scheme in **Figure 16.5**, suppose that the ethanol produced (666,933 L) with the ethanol lost in the vinasse and flegmasse (5,869 L) equals the volume of ethanol sent to the distillation columns. Calculating the amount of TRS lost in the distillation process is possible.

TRS sent to distillation = TRS in ethanol + TRS lost in vinasse and flegmasse
= 1,029,218 + 9,057 = 1,038,275 kg

The TRS in ethanol (666,933/ 0.6480 = 1,029,218 kg) was calculated in Chapter 14.4 "Ethanol production". The total "TRS in ethanol" in-

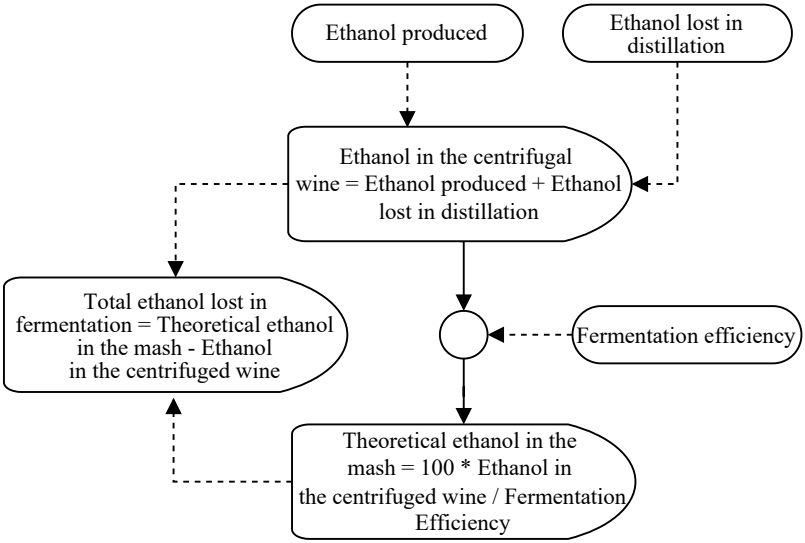
Ethanol produced
Ethanol lost in distillation
Ethanol in the centrifugal wine = Ethanol produced + Ethanol lost in distillation
Total ethanol lost in fermentation = Theoretical ethanol in the mash - Ethanol in the centrifuged wine
Fermentation efficiency
Theoretical ethanol in the mash = 100 * Ethanol in the centrifuged wine / Fermentation Efficiency

Figure 16.5 – Total ethanol lost in the fermentation process, (by an alternative calculation).

cludes all ethanol produced and converted at 100% (685,240 L), distillery in-process variation including theoretical ethanol in molasses (33,572 L), reprocessed ethanol (25,000 L), virtual molasses from the sugar in-process, molasses input and output, and other intermediate products.

The TRS lost in vinasse and flegmasse (5,869/ 0.6480 = 9,057 kg) was calculated in item 16.4; "Distillation control", sub-item "TRS loss in distillation".

One more step back: Fermentation produced the TRS in the ethanol sent to the distillery. Therefore, by dividing this amount of TRS by the efficiency of batch (88.91%) or continuous (90.41%) fermentation, the TRS (kg) in the mash is obtained. In the example:

Theoretical TRS in mash = 100 ∗ TRS in ethanol / Fermentation Efficiency
= 100 ∗ 1,038,245 / **88.91** = 1,167,782 kg

The difference between TRS in the mash and TRS sent to distillation represents the total amount of TRS lost in fermentation.

TRS lost in batch fermentation = Theoretical TRS in mash - TRS sent to distillation
= 1,167,782 - 1,038,275 = 129,507 kg

The calculation before can be summarised in only one formula (Fernandes, 2011):

TRS lost in fermentation = TRS sent to distillation ∗ (100 / Fermentation Efficiency - 1)

Thus, the calculation of TRS lost in fermentation is performed for batch fermentation:

Losses of TRS in fermentation = TRS sent to distillation ∗ (100 / Fermentation Efficiency - 1)
= 1,038,275 ∗ (100 / 88.91 - 1) = 129,507 kg

The "fermentation efficiency" can be the mean result of the day or period for a batch system, as used in the example, or for a continuous system. The same criteria are valid for both methods.

16.6 Controls for batch fermentation

The controls suggested below will allow tracking of fermentation and yeast treatment times and may explain underperformance occurrences. In MS-Excel® format cells with hours (hh:mm) in [h]:mm.

Control of batch fermentation times, time notations and calculations

- Note the start and end times of mash feeding per vat
- Note the end time of fermentation.
- Note the start and end times of the centrifugation of the raw wine.

Calculate:

Total feed time = Start time of mash feeding - End time of mash feeding

Fermentation time = End time of fermentation - Start time of mash feeding

Wait time for centrifuge = Start time of raw wine centrifugation - End time of fermentation

Total centrifuge time = Start time of raw wine centrifugation - End time of raw wine centrifugation

Yeast treatment controls, time notations and calculations

- Note the start and end time of yeast treatment.
- Note the time when the vat was sent to the fermentation vessel.
- Record the volumes of water and acid added to the yeast.
- Calculate total yeast treatment time, from waiting to being sent to the fermentation vessel.

16.7 Distillery Overall Efficiency

The Distillery Overall Efficiency (DOE) is the percentage ratio of the total "ethanol produced" to the total "theoretical ethanol in the mash". For "ethanol produced", variations in ethanol in-process and ethanol due to input and/or output molasses must be considered, as well as

input and/or output of other intermediate products from the distillery, such as syrup, dry yeasts, and yeast cream. In the example, the volume of "ethanol produced" was previously calculated as 666,933 L.

The volume of the "Theoretical ethanol in the mash" was calculated as:

Theoretical ethanol in the mash = Total TRS in the mash ∗ 0.6480
= 1,152,549 ∗ 0.6480 = 746,852 L

Note: For **continuous fermentation**, the calculation of the theoretical volume of ethanol in the mash is described in item: 16.3 "The continuous fermentation process".

Theoretical ethanol in the mash = Total TRS in the mash ∗ 0.6480
= 1,148,433 ∗ 0.6480 = 744,185 L

Distillery Overall Efficiency will be obtained by multiplying the Fermentation Efficiency by the Distillation Efficiency:

Distillery Overall Efficiency = Fermentation efficiency ∗ Distillation efficiency / 100
= 88.91 ∗ 99.13 / 100 = **88.14%**

These calculations do not include the "indeterminate losses" that occur in the distillery process, which are incorporated into the "indeterminate losses" in the overall TRS mass balance of the joint sugar/ ethanol processes.

Continuous Distillery Overall Efficiency Example

Distillery Overall Efficiency = Continuous Fermentation Efficiency ∗ Distillation efficiency / 100
= 89.56 ∗ 99.13 / 100 = **88.78**%

16.8 Efficiency of raw wine centrifuges

Example data and calculations:

Yeast % raw wine	14.5%
Yeast % centrifuged wine	0.7%
Yeast % yeast cream	55.0%

Yeast loss % raw wine = 100 * Yeast % centrifuged wine * (Yeast % yeast cream - Yeast % raw wine) / (Yeast % raw wine * (Yeast % yeast cream - Yeast % centrifuged wine))
= 100 * 0.7 * (55.0 - 14.5) / (14.5 * (55.0 - 0.7)) = **3.6**%

Efficiency of raw wine centrifuges = (100 * (1 - Yeast % centrifuged wine * (Yeast % yeast cream - Yeast % raw wine) / (Yeast % raw wine * (Yeast % yeast cream - Yeast % centrifuged wine)))
= (100 * (1 - 0.7 * (55.0 - 14.5) / (14.5 * (55.0 - 0.7))) = **96.4**%

17 TRS balance

When the accumulated Total Recovery of TRS for the entire harvest is below its expected value, it is expedient to adopt some additional procedures. These can include:

- Check and validate all data entered in the system, total cane processed, and amounts of sugar, ethanol, and other by-products.
- Confirm the analytical data, mainly on the cane technological quality, and compare it to the results from the previous periods.
- Revalidate the data from the survey of the material in-process (sugar and ethanol) and compare it with previous periods.
- Check the formulas and calculations performed in the industrial process control system (software).
- Study the results of "Mass Balance of TRS", focusing mainly on the undetermined losses of TRS.

17.1 Total losses of TRS

For traditional mills that exclusively produce sugar and technically (and economically) exhausted molasses, the balance of sugar losses can be carried out in terms of "pol", though it is preferable to do so in terms of "sucrose".

However, for Brazilian plants that produce sugar and ethanol simultaneously from the same raw material, the balance of losses must be carried out in terms of "total reducing sugars" (TRS). The following discussion focuses on the losses of TRS in such factories.

See Chapter 15 "Factory yield and efficiency" for the origin of nominated values in the following calculations.

Informed values:

Milled cane	13,398.324 t

See Chapter 7.4 “Cane press method calculations”:

Fiber % cane 12.13%
Pol % cane 14.45%
TRS % cane 15.77%

Reducing sugars % cane = TRS % cane - Pol % cane/ 0.95
= 15.77 - 14.45/ 0.95 = 0.56%

Cane purity= 100 * Pol % cane/ Brix % cane
= 100 * 14.45/ 17.31 = 83.5%

TRS lost in wastewater

When the “undetermined losses of TRS % TRS cane”, accumulated in the season, are below 1%, which is not common, and the Fermentation Efficiency is around 90%, and there are no resources available, the survey of TRS losses in wastewater would have to be dispensed with.

If the undetermined losses are above 3% or 4%, and all the items mentioned above have been verified, it is recommended to proceed with the determination of TRS lost in wastewater.

Example calculations:

TRS lost in water = Loss in sugarcane washing + Loss by entrainment in the vapor condensers + Loss from leakage in pipes and ducts
= 0 + 0 + 0 = 0 kg

In this example, the TRS losses were not measured in the wastewater.

The main difficulty in determining the total amount of sugar lost in wastewater consists of measuring the volumes of water from vapor condensers, washing equipment, water channels, and other flows.

The TRS or total carbohydrate content of wastewaters can be obtained by several methodologies, such as anthrone, Lane & Eynon, Somogyi & Nelson, and chromatography.

TRS losses in bagasse

According to previous information in Chapter 11.7 "Sampling and analysis of final bagasse":

Fiber % bagasse	47.17%
Pol % bagasse	1.50%
TRS % bagasse	1.70%
Moisture % bagasse	50.7%

Example calculations:

Bagasse yield = 100 * Fiber % cane / Fiber % bagasse
= 100 * 12.13 / 47.16 = 257.21 kg/t cane

Produced bagasse = Milled cane * Bagasse yield
= 13398.324 * 257.21= 3,446,183 kg

TRS % bagasse estimated = 1.04 * Pol % bagasse * TRS % cane / Pol % cane
= 1.04 * 1.50 * 15.77 / 14.45 = 1.70%

TRS lost in bagasse = Produced bagasse * TRS % bagasse / 100
= 10 * 3,446.183 * 1.70 = 58 585 kg

TRS losses in the filter cake

See Chapter 11.8 "Sampling and analysis of filter cake".

Example calculations:

Produced filter cake (informed)	395.00 t
Pol % ilter cake (determined)	2.40%

TRS % filter cake (estimated) = Pol % filter cake * TRS % cane / Pol % cane
= 2.40 * 15.77 / 14.45 = 2.62%

TRS lost in filter cake = 10 * Produced filter cake * TRS % filter cake
= 10 * 395.00 * 2.62 = 10,349 kg

Note that the results of TRS % bagasse and TRS % filter cake do not need to be analytically determined, since they can be estimated as shown in previous items.

TRS lost in batch fermentation, an example calculation

As demonstrated before:

TRS sent to distillation = TRS in ethanol + TRS lost in vinasse and flegmasse
= 1,029,218 + 9 057 = 1,038,275 kg

The "TRS lost in fermentation" can be calculated by the formula:

TRS lost in fermentation = TRS sent to distillation * (100/ Fermentation Efficiency - 1)
= 1,038,275 * (100 / 88.91 - 1) = 129,507 kg

See Chapter 16.2 "The traditional batch fermentation" for the deduction of this formula (Fernandes,2011).

TRS lost in distillation, an example calculation

The theoretical volume of ethanol lost by distillation was calculated in the chapter "Distillation control" and resulted in:

Ethanol lost distillation = ethanol lost vinasse + ethanol lost in flegmasse mass
= 5,709 + 160 = 5,869 L

TRS lost in distillation = Ethanol lost in distillation / 0.6480
= 5,869 / 0.6480 = 9,057 kg

Although there are other losses in distillation, for practical purposes only the vinasse and flegmasse losses should be considered, as calculated in "Distillation control".

Determined losses of TRS, an example calculation

Determined losses of TRS = Water + Bagasse + Filter cake + Fermentation + Distillation
= 0 + 58 585 + 10 349 + 129,507 + 9 057 = 207,498 kg

Total losses of TRS, an example calculation

Total losses of TRS = TRS in cane - TRS in sugar and ethanol produced
= 2,112,916 – 1,872,680 = 230,611 kg

Undetermined losses of TRS, an example calculation

Undetermined losses of TRS = Total losses of TRS - Determined losses of TRS
= 230,611 – 207,498 = 23,113 kg

TRS lost in Wastewater, Bagasse, Filter cake, and Undetermined (WBFU)

WBFU losses of TRS = Sum of losses in (Water, Bagasse, Filter cake, Undetermined)
= 0 + 58,585 + 10,349 + 23,113 = 92,047 kg

As stated before, the term WBFU = Losses of Total Reducing Sugars (TRS) that occur in the common phase of sugar and ethanol manufacturing, including wastewater (W), bagasse (B), filter cake (F), and undetermined (U). In the Brazilian Consecana-SP sugarcane payment

system, these losses are set at the fixed value of 8.5% of the total TRS in sugarcane.

17.2 Losses of TRS % TRS in cane, example calculations

In the item "Milling calculations" the "Totals TRS in crushed cane" were calculated, with the total TRS equal to 2,112,715 kg. The losses calculated in the previous item divided by the total TRS in the sugarcane result in the percentage of TRS losses.

Total TRS losses % TRS cane = 100 * Total TRS losses / TRS in cane
= 100 * 240,236 / 2,112,916 = 10.91%

TRS lost water % TRS cane = 100 * TRS lost water / total TRS cane
= 0.00% (not determined in this example)

TRS bagasse % TRS cane = 100 * Losses TRS bagasse / total TRS cane
= 100 * 58,585 / 2,112,916 = 2.77%

TRS lost in filter cake % TRS in cane = 100 * TRS lost in filter cake / TRS in cane
= 100 * 10,349 / 2,112,916 = 0.49%

TRS lost in fermentation % TRS in cane = 100 * Losses TRS fermentation / TRS in cane
= 100 * 129,507 / 2,112,916 =6.13%

TRS lost in distillation % TRS in cane = 100 * TRS lost in distillation / TRS in cane
= 100 * 9,057 / 2,112,916 = 0.43%

Determined losses of TRS % TRS in cane = 100 * Determined losses TRS / TRS in cane
= 100 * 207,498 / 2,112,916 = 9.82%

Undetermined losses TRS % TRS in cane = 100 ∗ Undetermined losses TRS/ TRS in cane
= 100 ∗ 23,113/ 2,112,916 = **1.09**%

WBFU losses % TRS in cane = 100 ∗ WBFU losses of TRS / TRS in cane
= 100 ∗ 9,047 / 2,112,916 = 4.36%

The interpretation of TRS losses

The "Undetermined losses of TRS % TRS in cane", together with the Total Recovery and Fermentation efficiency (FE), allows the effective evaluation of the performance of the industrial process.

It is important to always check weekly or fortnightly total TRS loss values together with the results accumulated in the season. The daily results fluctuate quite a lot due to the variability of data from the survey of in-process sugar and ethanol and inaccuracy in determining the TRS % cane.

The **undetermined losses** TRS % TRS in cane for the whole crop in Brazil can be classified into:

- ✓Up to 1.0% Excellent (rare)
- ✓1.0 a 2.0% Great
- ✓2.0 a 3.0% Good (more common)
- ✓3.0% a 4.0% Reasonable
- ✓Above 4.0% Bad

High values of undetermined losses are often associated with overestimated fermentation efficiency. The reverse is also true. Another reason for high losses is related to the incorrect assessment of the cane's TRS value. Note that undetermined losses include losses at both the sugar factory and the distillery.

When the Total Recovery of TRS in the factory is high, around 90% (where sugar production is above 60% of the production mix), undetermined losses are usually low. When TRS total recovery is low undetermined losses are usually high.

In some situations, undetermined losses are above 5% in the accumulated season. If such high undetermined losses exist, most of these losses will be visible, such as leaks or entrainment in vapors, or they will originate in undetected factory process control errors.

17.3 Losses of TRS per ton of cane (kg/t cane), example calculation

Total losses of TRS /t cane = Total losses of TRS / Milled cane
= 230,611 / 13,398.324 = 17.21 kg/t cane

TRS lost in wastewater/t cane = TRS lost in wastewater / Milled cane
= not determined in this example = 0.00 kg/t cane

TRS lost in bagasse/t cane = TRS lost in bagasse/ Milled cane
= 58,585 / 13,398.324 = 4.37 kg/t cane

TRS lost in filter cake/t cane = TRS lost in filter cake / Milled cane
= 10,349/ 13,398.324 = 0.77 kg/t cane

TRS lost in fermentation/t cane = TRS lost in fermentation / Milled cane
= 129,507 / 13,398.324 = 9.67 kg/t cane

TRS lost in distillation /t cane = TRS lost in distillation / Milled cane
= 9,057 / 13,398.324 =0.68 kg/t cane

Determined losses of TRS/t cane = Determined losses of TRS / Milled cane
= 207,498 / 13,398.324 = 15.49 kg/t cane

Undetermined losses of TRS /t cane = Undetermined losses of TRS / Milled cane
= 23 113 / 13 398.324 = 1.73 kg/t cane

TRS lost in Water, Bagasse, Filter cake, and Undetermined (WBFU)
= WBFU losses of TRS / Milled cane
= 92,047 / 13,398.324 =. 6.87 kg/t cane

Preferably, TRS losses should be expressed as a percentage of the total TRS of the processed cane. The values in "kg/t cane" units should be divided by 10 to convert them to" % on cane" units.

18 Corrected sugar (RIC) and ethanol yield

The calculations presented in this chapter are theoretical and apply only to sugar/ethanol plants in Brazil.

Before the mid-1970s, Brazilian sugar mills with attached distilleries produced "residual ethyl ethanol" from final molasses, that had a low purity as it had been technically and economically "exhausted".

Following the implementation of the National Alcohol Program (Proálcool) in 1976, sugar ethanol companies started investing in increasing distillery production capacity and shifting some secondary and primary juice to ethanol production.

Most mills stopped exhausting the final molasses and switched from the three-massecuite boiling system to the two-massecuite system. The molasses from the second boiling (B-molasses) became known as "final molasses".

At the same time, industrial units called "autonomous distilleries" were built in various regions of Brazil to produce "direct hydrous ethanol" directly from cane without the sugar manufacturing stage.

The area of harvested cane increased from two million hectares in 1976 to eight million hectares in 2022, resulting in higher production of cane, sugar, and ethanol (**Figure 18.1**).

Due to this situation, it becomes necessary to use theoretical formulas for estimating sugar (kg/t cane) and ethanol (L/t cane) yield, from an unsolvable situation of "one equation with two unknown figures":

Total cane milled = Cane milled for sugar + Cane milled for ethanol

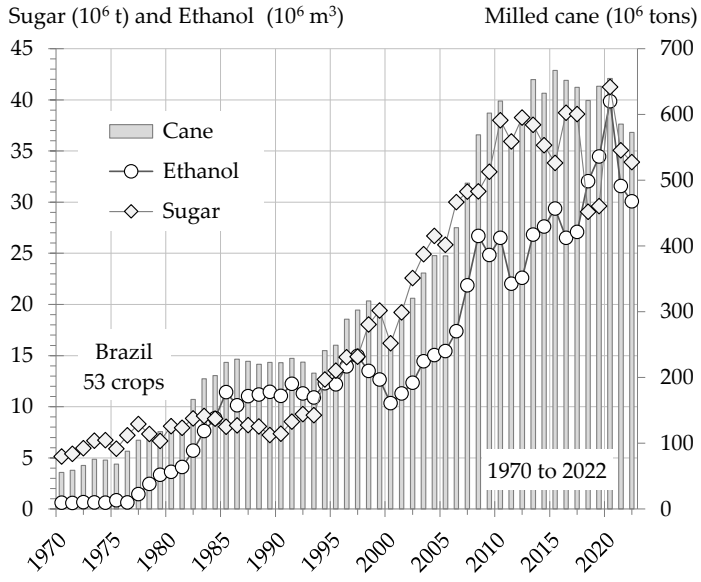

Figure 18.1 – Milled sugarcane, sugar, and ethanol production in Brazil since 1970 (several sources).

18.1 Corrected industrial yield

In 1933, the Federal Government of Brazil created the Sugar and Alcohol Institute (Portuguese "Instituto do Açúcar e do Álcool" - IAA), a federal agency of the Ministry of Industry and Commerce. This administrative body was responsible for regulating and promoting the production, transport, and trade of cane, sugar, and ethanol, including matters relating to production quotas, taxes, and fees, setting purchase and sale prices for the industry and the consumer. However, in the nineties, the IAA was extinguished, and the industry was deregulated.

In 1981 the IAA issued Resolution 09/81 with its "official" formula for calculating industrial yield, discussed in this chapter because of its historical value and because it is the basis for calculations and inspired

concepts of some formulas. The "corrected industrial yield" (RIC) was introduced to allow comparison with other crop seasons or between producing units as well as to allow estimates of the quantities of cane processed to produce the sugar and ethanol in the production mix.

Note: The **RIC** symbol is kept here for consistency as it is a historical value in Brazil.

18.2 Definition of the technical parity ratio

To calculate the RIC, it is necessary to know the "technical parity ratio", which was originally defined by the MIC-IAA as *"the volume of direct anhydrous ethanol at 99.3%$_{m/m}$ at 20 oC temperature that can be produced from a certain amount of cane which, if used to produce sugar in a plant with an attached distillery, will result in the production of a standard crystal sugar bag 60 kg with 99.3 °S of pol and the corresponding volume of residual anhydrous ethanol at 99.3%$_{m/m}$ from the final molasses"*.

Historical data in Brazil

In surveys of the final molasses analysis, exported by the northeast region of Brazil in the 1970s, some values obtained were considered standards for that time. These were:

a) For each 60 kg bag of sugar, 23.65 kg of molasses were produced (0.3942 kg molasses/kg of sugar).
b) The mean TRS content of molasses was 55.0%.
c) This molasses sent to the distillery produced 7.0 L of anhydrous ethanol, denominated "residual ethanol", (99.3%$_{m/m}$ and specific mass equal to 791.42 kg/m^3).
d) The mean yield at that time for the Center-South region of Brazil was 94.0 kg of standard crystal sugar (99.3 °S) per ton of cane. The standard mean yield for the North-Northeast of Brazil was 90.0 kg/t cane.

e) From the previous values, the yield of molasses in the Center-South region was 37.05 kg/t cane (23.65 ∗ 94.0 / 60).

In the South African mills, between 2001 and 2017, the mean production of molasses 85% brix was 42 kg/t cane (variation between 37 and 47 kg molasses/t cane). A mean of 0.3625 kg of molasses per kg of sugar was produced, compared to 0.3942 kg molasses/ kg standard sugar in Brazil, according to MIC-IAA, 1981.

Distillery Overall Efficiency

a) The ratio of 7.0 L of anhydrous residual ethanol (from the final molasses associated with each 60 kg bag of standard sugar) is equivalent to 0.1167 L of anhydrous residual ethanol (99.3%m/m) per kilogram of standard crystal sugar 99.3 °S (7/60).
b) TRS in the final molasses per 60 kg bag of sugar: 23.65 ∗ 55% = 13.01 kg of TRS / 60 kg bag of sugar.
c) The overall distillery yield from the final molasses was obtained by 7.0 L / 13.01 kg TRS = 0.5380 L anhydrous ethanol/kg TRS.
d) The distillery's overall efficiency based on final molasses was 100 ∗ 7.0 / (23.65 ∗ 0.55 ∗ 0.6508) = 82.69%, where the factor 0.6508 represents the stoichiometric transformation of TRS into anhydrous ethanol (99.3%m/m) according to Bettin & Spieweck (1990). The distillery efficiency obtained in the early 1970s is a low value for today's conditions, even for low-purity molasses.

Technical parity ratio

As previously defined, the "technical parity ratio" between sugar and ethanol was calculated from the basic parameters established by the MIC-IAA in the previous item.

a) The total reducing sugars (TRS) contained in a 60 kg bag of crystal standard sugar 99.3 °S is 62.72 kg [60 ∗ 99.3 / 95].

b) Thus, a bag of sugar (60 kg) corresponds to 33.74 L anhydrous ethanol/60 kg bag of sugar (0.5380 ∗62.72).

This transformation does not mean that a bag of sugar was dissolved to ferment since it would not produce the same results due to the lack of nutrients in this "virtual mash". This calculation corresponds to the portion of sucrose in the raw material (juice and/or molasses) that was used to produce sugar, hydrolyzed, and converted into ethanol.

a) Adding the 33.74 L of anhydrous ethanol, that is, "ethanol from sugar", to the 7.0 L of residual ethanol from molasses, yields the parity ratio as **40.74 L of anhydrous ethanol per 60 kg bag of white standard sugar**. Conversely, **0.6790** L anhydrous ethanol/kg sugar (40.74/ 60)

18.3 Deduction of the RIC formula by IAA (1981)

To calculate the amount of "cane for sugar" and "cane for ethanol" it is important to understand or remember the RIC paradigm and its importance for the sugar and ethanol sector. The RIC theoretically indicates what the sugar yield (kg/t of cane) would be obtained if the plant worked to produce sugar and final molasses technically and economically exhausted.

Therefore, some assumptions needed to be established, such as quantity and TRS content of the molasses, Overall Distillery Yield (L ethanol/ kg TRS), to calculate the amount of "residual" ethanol that could have been produced with the low-purity molasses, and the "technical parity relationship" between sugar and ethanol, as previously defined.

Note that the ethanol was produced from two sources: (1) the juice diverted from the mill or diffuser to the distillery and (2) from the molasses, the latter being called **residual ethanol** (**Figure 18.2**).

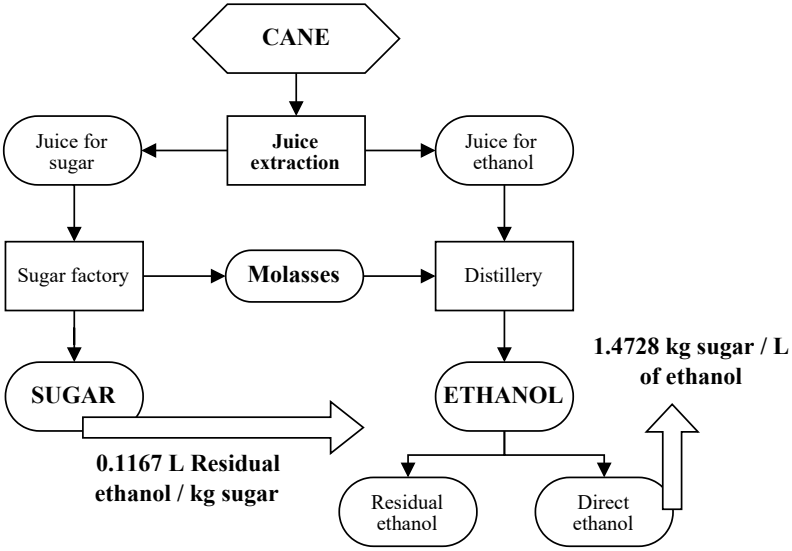

Figure 18.2 – Parity ratio between sugar, residual-ethanol, and direct-ethanol, according to MIC-IAA (1981).

Calculation of RIC

Subtracting the residual ethanol from the total ethanol produced gives the volume of ethanol due to the cane juice deviating to the annexed distillery. This volume divided by the "Parity Ratio" results in the sugar corresponding to the "cane for sugar".

This sugar must be added to the sugar produced and the total divided by the milled cane in the same period to result in the "Corrected Sugar Yield" (RIC) in kilograms of sugar 99.3 °S per ton of cane.

RIC = (Sugar + (Total ethanol - Residual ethanol) / Parity Ratio) / Milled cane

Where some definitions are:

Sugar 99.3 °S: Total sugar produced plus in-process variation of standard white sugar of pol 99.3 °S (kg).
Total ethanol: Total anhydrous ethanol 99.3%m/m produced from the final molasses and the juice sent to the distillery (L).
Residual ethanol: theoretical volume of anhydrous ethanol $99.3\%_{m/m}$ from the molasses of processed cane (L).
Parity Ratio: "The volume of ethanol that can be produced in an autonomous distillery from a certain amount of cane which, if used to produce sugar in a plant with an attached distillery, will result in the production of 1.0 kg of sugar and the corresponding volume of residual ethanol from the final molasses".
Milled cane: Cane processed at the same time as sugar and ethanol production (t).

Estimation of anhydrous residual ethanol with example calculation

The volume of residual ethanol, from the consumed molasses, is an unknown value that can be estimated considering a ratio of "liters of residual ethanol per kilogram of sugar 99.3 °S".

Anhydrous residual ethanol = Residual ethanol ratio * Sugar

RIC = (Sugar + (Total ethanol - Residual ethanol ratio * Sugar)/ Parity Ratio) / Milled cane

Simplifying the previous equation to obtain the ***generic formula of RIC***:

RIC = ((1 - Residual ethanol ratio / Parity Ratio) * Sugar + (1 / Parity Ratio) * Ethanol) / Milled cane

Considering the values established by MIC-IAA in 1981:

Residual ethanol ratio = Final molasses per bag 60 kg of sugar * TRS % molasses / 100 * Overall Distillery Yield / Standard sugar

$= 23.65 * 55.0 / 100 * 0.5380 / 60.0 = 0.1167$ L ethanol/kg sugar 99.3 °S

This result is the same as 7.0 L of anhydrous ethanol ($99.3\%_{m/m}$) per 60 kg bag of standard crystal sugar 99.3 °S (7/60=0.1167 L/kg).

The "Parity Ratio"

As defined previously, the "Parity Ratio" found by MIC-IAA in 1981 is **40.74 L of anhydrous ethanol per 60 kg bag of white standard sugar** (**Figure 18.3**).

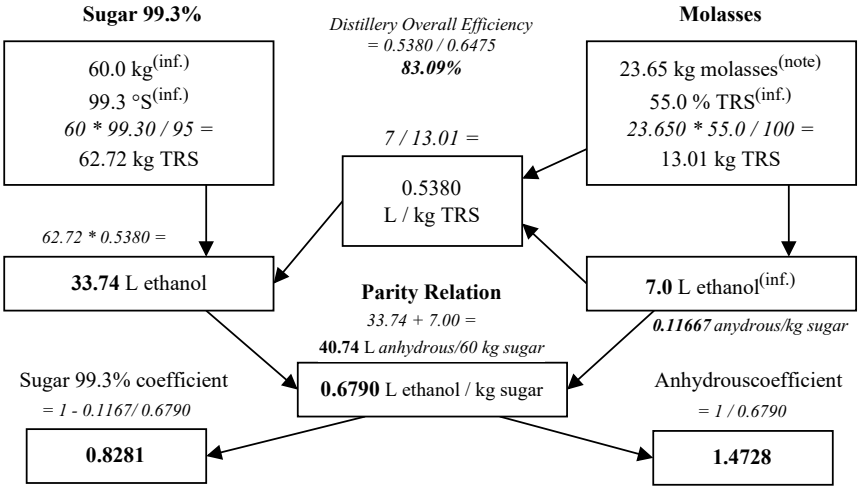

Figure 18.3 – Parity ratio between sugar, residual-ethanol, and direct-ethanol, according to MIC-IAA (1981). (*inf.*) = *informed value.* (*note*) *kg of molasses per kg of sucrose in sugar.*

RIC formula by MIC-IAA, 1981 calculation

Knowing the residual anhydrous ethanol ratio with standard sugar (0.1167 L/kg) and the parity ratio (0.6790 L direct anhydrous ethanol/ kg standard sugar) it is possible to calculate the RIC.

RIC = ((1 - 0.1167 / 0.6790) ∗ Standard Sugar + (1 / 0.6790) ∗ Anhydrous Ethanol) / Milled cane

Simplifying to obtain the original RIC-IAA formula of 1981:

RIC = (0.8281 ∗ Standard Sugar + 1.4728 ∗ Anhydrous Ethanol) / Milled cane

18.4 RIC for sugar 100% and ethanol 100%

To be more coherent with the other calculation results, the RIC can be obtained from the total production of sugar converted at 100% according to the pol of each type of sugar and from ethanol at 100% obtained by the sum of the different types of ethanol according to the alcoholic strength by mass ($\%_{m/m}$) and respective density in kg/m^3 (**Figure 18.4**).

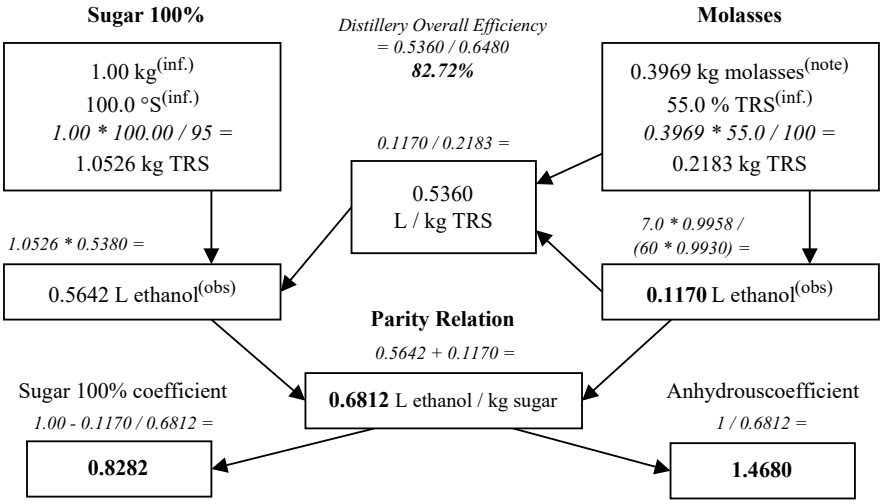

Figure 18.4 – Deduction of "Parity Ratio" between sugar anethanol (MIC-IAA, 1981). (*inf.*) *informed value.* (*note*) *kg of molasses per kg of sucrose in sugar*.

From the generic equation for RIC:

$$RIC_{100\%} = ((1 - \text{Residual ethanol ratio}/ \text{Parity Ratio}) * \text{Sugar} + (1 / \text{Parity Ratio}) * \text{Ethanol}) / \text{Milled cane}$$
$$= ((1 - 0.1170/ 0.6812) * \text{Sugar} + (1 / 0.6812) * \text{Ethanol}) / \text{Milled cane}$$

Simplifying:

$$RIC_{100\%} = (0.8282 * \text{Sugar} + 1.4680 * \text{Ethanol}) / \text{Milled cane}$$

This calculation does not use raw material quality data, such as pol % cane, fiber % cane, and juice purity. It only uses the total amounts of crushed cane, the sugar produced, and the ethanol produced.

18.5 Example of RIC calculation

The yields obtained from sugar and ethanol are stoichiometrically converted into standard sugar 100% and anhydrous ethanol $100\%_{m/m}$. Nominating example data for a day:

Milled cane	13,398.324 t
Produced sugar	810,433 kg
Produced ethanol	666,933 L

Corrected sugar yield 100%

$$RIC_{100\%} = (0.8282 * \text{Sugar} + 1.4680 * \text{Ethanol}) / \text{Milled cane}$$

$$\text{Total } RIC_{100\%} = (0.8282 * \text{Sugar} + 1.4680 * \text{Ethanol})$$
$$= 0.8282 * 810{,}433 + 1.4680 * 666{,}933 = 1{,}650{,}258 \text{ kg}$$

$$\text{“Corrected factory yield” } (RIC_{100\%}) = \text{Total } RIC_{100\%} / \text{Milled cane}$$
$$= 1{,}650{,}258 / 13{,}398.324 = \mathbf{123.17\ kg/t\ of\ cane}$$

The result of the $RIC_{100\%}$ means that, if this industrial unit in the example worked with the exclusive production of sugar and final molasses with a purity equal to or lower than 40%, the sugar yield (100%) would be 123.17 kg/t cane.

The Overall Factory Recovery using RIC

Overall Factory Recovery = 100 * Total $RIC_{100\%}$ / Total pol in milled cane
= 100 * 1,650,258 / 1,936,058 = **85.24%**

In South African sugar mills, this efficiency is called "Overall Recovery" (O.R.), and the arithmetic mean of the 14 sugar mills in the 2001 to 2017 harvests was **84.91%**, with a variation between harvests of 81% to 87%, which can be accepted as a high-performance threshold. The mean sucrose % cane of these factories and crops was 13.55% varying from 12.92% to 14.25%.

18.6 Cane for sugar and cane for ethanol, an example calculation

The RIC is also used to estimate the amount of "**cane for sugar production**". This calculation was used to pay taxes and government fees, which are different values for " cane for sugar" compared to "cane for ethanol".

Total cane milled = Cane milled for sugar + Cane milled for ethanol

Cane milled for ethanol = Total cane milled - Cane milled for sugar

Cane for sugar = Produced sugar / $RIC_{100\%}$
= 810,433 / 122.81 = 6,580 t

Cane for ethanol = Total milled cane - Cane for sugar
= 13,398.324 - 6,580 = 6,819 t

Cane for sugar % Total milled cane = 100 ∗ Cane for sugar / Milled cane
= 100 ∗ 6 819 / 13,398.324 = **49.11**%

Cane for ethanol % Total milled cane = 100 - Cane for sugar % milled cane
= 100 - 49.11 = **50.89**%

18.7 Corrected yield of ethanol

As mentioned previously, a sugar and ethanol-producing plant obtains its total ethanol from two sources. Firstly, the juice and other products from the sugar plant are sent to the distillery. Secondly, the molasses is used to produce ethanol, known in Brazil as "residual ethanol" (**Figure 18.2**).

The volume of residual ethanol is an unknown value since it is effectively mixed with the ethanol from the juice sent to the distillery. For this reason, the ethanol obtained from the final molasses must be estimated by evaluating a ratio with the produced sugar in "L ethanol/ kg of sugar".

The calculation using the MIC-IAA 1981 model assumes that for each kilogram of sugar, 0.1170 L residual 100% ethanol would have been produced, arising from the associated molasses with 40% apparent purity and 55% TRS. This ratio can vary between 0.1000 and 0.1200 L residual ethanol/ kg of sugar.

For each kg of sugar, 0.3969 kg of molasses 40% purity, and 55% of TRS would have been produced:

Distillery Overall Yield = Residual ethanol per kg of sugar (in 60 kg bags)
= 7.0 ∗ 0.9958 / (60 ∗ 0.993) = 0.5390 L ethanol/kg sugar

Where 0.9958 is the conversion coefficient from anhydrous to 100% ethanol. The coefficient 0.993 accounts for the polarization of standard white sugar.

Distillery Overall Efficiency = Distillery Overall Yield / 0.6480
= 0.5360 / 0.6480 = **82.72**%

Where 0.6480 is the stoichiometric coefficient (L of ethanol/ kg of TRS).

The ethanol produced from a molasses with 40% of apparent purity:

Relation residual ethanol and sugar = Molasses (kg/kg sugar) ∗ TRS % molasses / 100 ∗ Distillery Overall Efficiency / 100
= 0.3969 ∗ 55% ∗ 0.6480 ∗ 82.72% = 0.1170 L/kg

Residual ethanol = **0.1170** ∗ Produced sugar
= 0.1170 ∗ 810,433 = 94,821 L

Residual ethanol yield = Residual ethanol/ Cane for sugar
= 94,821 / 6,580 = 14.41 L/t cane for sugar

Direct ethanol = Produced ethanol - Residual ethanol
= 666,933 - 94,821 = 572,112 L

Direct ethanol yield = Direct ethanol / Cane for ethanol
= 572,112 / 6,819 = **83.91** L/t cane for ethanol

These results mean that, if this industrial unit worked with the exclusive production of ethanol directly from the juice, the yield would be 83.91 L/t cane.

The calculation presented here is not part of MIC-IAA 1981 RIC. It was deduced later based on the same principle.

18.8 Production mix and cane for sugar

The "production mix" (MIX), as calculated previously (*Effective yield of sugar and* ethanol), does not represent the percentage of cane for sugar or ethanol, although it has a high significative linear regression with "cane for sugar RIC".

Why? Because part of the total ethanol produced came from the molasses of cane used for sugar production, which in turn depends on the molasses purity and exhaustibility.

The production mix (TRS in sugar % TRS in sugar and ethanol) is normally used to indicate whether the mill is primarily working as a sugar producer (MIX > 50%) or as an ethanol producer.

Example calculation of sugar yield according to the MIX of products (an incorrect method!)

Using the previously calculated data:

Cane for sugar (mix) = Milled cane * TRS in sugar % total TRS produced / 100
= 13,398.324 * 45.32 / 100 = 6,072.120 t cane

Sugar yield per cane mix = Total sugar/cane for sugar mix
= 810,433 / 6,072.120 = **133.47** kg sugar/t cane

Overall Factory Recovery (mix) = 10 * Sugar yield per cane MIX/ Pol % cane
= 10 * 133.47 / 14.45 = **92.37**%

As it is not technically possible to achieve an Overall Recovery of 92.37% with current technology, this example shows that "cane for sugar (mix)" cannot be the lower value of 6,072 t (45.32% of total cane), but is the higher value 6,580 t (49.11%).

Note that the "sugar in the mix" is **45.32**%, but the "cane for sugar production" is **49.11**%. This means that 6,580 t of cane would be needed to produce 816,146 kg of standard sugar and molasses with an apparent purity of 40%.

The conclusion is that the calculation presented in "*Cane for sugar and cane for ethanol*" according to IAA 1981, is the correct method of estimating the "Cane for sugar % Total milled cane" (**49.53**%).

"Cane for sugar RIC" and production mix for sugar (TRS of sugar produced % total TRS of products) are highly correlated, but not equal values.

Example calculation of ethanol yield from the mix (an incorrect method)

This calculation is supposed for an autonomous distillery, i.e., a plant that produces only ethanol from sugar cane.

Cane for ethanol (mix) = Milled cane - Cane for sugar (mix)
= 13,398.324 - 6,072.120 = 7,326.204 t cane

Ethanol yield (mix) = Ethanol/ Cane for ethanol (mix)
= 666 933/ 7 326.204 = 91.03 L/t cane

Theoretical ethanol in cane = 10 * TRS % cane * 0.6480
= 10 * 15.77 * 0.6480 = 102.19 L/t cane

Distillery Overall Recovery (mix) = 100 * Ethanol yield (mix) / Theoretical ethanol in cane
= 100 * 90.56/ 102.19 = **89.08**%

In this example, the total losses in an autonomous distillery mix would be 10.92% (100 - 89.08) of distillery losses in milling, juice treatment, wastewater, fermentation, and distillation, undetermined. This value is too low and technically very unlikely.

The term "Cane for sugar" refers to the cane (t) needed to fabricate the effectively produced sugar (kg) when working with molasses of low purity (three-mass system). To calculate this quantity of cane, it is necessary to determine the Corrected Industrial Yield (RIC) according to the MIC-IAA of 1981, considering an apparent purity of the molasses of 40%.

The "mix for sugar" indicates the percentage of "total reducing sugars" (TRS) produced with sugar and ethanol. As previously calculated in Chapter 15.2 "Effective yield of sugar and ethanol" TRS in the product % total TRS produced.

The "TRS in sugar" (853,087 kg) only comes from the juice extracted from the cane and used to produce sugar, usually "primary juice." On the other hand, the "TRS in ethanol" (1,029,218 kg) was produced with the juice sent to the distillery (secondary juice) and from the molasses. Therefore, using "mix for sugar" to calculate the "cane for sugar" underestimates the result and increases the sugar yield (kg/t cane).

In the example used in this publication:

Results	**RIC**	**MIX**	**Unit**
Corrected Factory Yield	123.17	133.47	kg/t cane
Overall Factory Recovery	85.24	92.37	%
Cane for sugar	6,580	6,072	t
Cane for sugar % total cane	49.11	45.32	%

References

Andrietta, M. G. S., Andrietta, S. R., & Stupiello, E. N. A. (2011). Bioethanol – What Has Brazil Learned About Yeasts Inhabiting the Ethanol Production Processes from Sugar Cane? In *Biofuel Production-Recent Developments and Prospects*. InTech. https://doi.org/10.5772/16572

Basso, L. C., Basso, T. O., & Rocha, S. N. (2011). Ethanol Production in Brazil: The Industrial Process and Its Impact on Yeast Fermentation. In M. A. Dos Santos Bernardes (Ed.), *Biofuel Production-Recent Developments and Prospects*. InTech. https://doi.org/10.5772/17047

Berding, N. (2010). Fibre determination by hydraulic pressing – Which method is correct? *Proceedings ASSCT*, *32*, 433–444.

Bettin, H., & Spieweck, F. (1990). A revised formula for the calculation of alcoholometric tables. *PTB-MITTEILUNGEN*, *100*(6), 457–460.

Birkett, H. (1998). *Core Sampling Recommended Procedures*. Audubon Sugar Institute Louisiana State University Agricultural Center.

Birkett, H., & Stein, J. (2007, February). *Core lab methods and interpreting grower sheets*.

Brokensha, M., King, S. L., & Lausse, J.P. (1976). Evaluation of the press method for cane analysis under South African conditions. *Proceedings of The South African Sugar Technologists' Association Annual Congress*, 212–219.

Buchanan, E. J., & Brokensha, M. A. (1974). *The application of direct cane testing to the South African sugar industry*. 1456–1468.

CONSECANA. (2006). *Manual de Instruções*.

CTICS. (2022). *Protocole Interprofessionel de Campagne Annee 2022*. Centre Technique Interprofessionnel de la Canne et du Sucre.

Deerr, N. (1911). *Cane sugar; a textbook on the agriculture of the sugar cane, the manufacture of cane sugar, and the analysis of sugar-house products*. London, N. Rodger.

Douwes-Dekker, K. (1961). The brix of the juice expressed from cane by static pressure. *Thirty-Fifth Annual Congress of the South African Sugar Technologists' Association*, 79–94.

FAO. (2020). Crops and livestock products. In *FAOSTAT*.

Foster, D. H. (1956). *Analytical methods used in assessing mill tandem performance*. 426–436.

Hengel, A. V. (1974). *Proposal for the identification of cane and sugar in identical units at standardised factory efficiency*. 1446–1455.

Hoarau, M. (1969). Sugar cane analysis by the hydraulic press method. *International Sugar Journal*, *71*, 328–332.

Hugot, E. (1974). *Direct analysis and evaluation of sugarcane. 15*, 1426–1436.

Lane, J. H. (1923). Determination of reducing sugar by means of Fehling's solution with methylene blue as internal indicator. *J. Soc. Chem. Ind.*, *17*, 32–37.

Legendre, B. L. (2010, February). *Interpretation of Mill Reports*.

Legendre, B. L., & Henderson, M. T. (1972). History and development of sugar yield calculations. *Proceedings-American Society of Sugar Cane Technologists*, *2*, 10–18.

Lemaire, Y. (1971). *Cane sampling by coring, hydraulic press, automatic saccharimetry*. 1626–1636.

Mackintosh, D. (2000). Sugar Milling. In M. Hogarth & P. Allsopp (Eds.), *Manual of canegrowing* ([New ed.]). Bureau of Sugar Experiment Stations.

OIML. (1973). *International Alcoholometric Tables*.

Payne, J. H., & Mahon, H. I. (1956). *The pol ratio method for evaluating cane quality*. 436–447.

Rein, P. (2017). *Cane Sugar Engineering* (Second edition). Verlag Dr. Albert Bartens KG.

Roussel, C. (2016). *Evaluation of sugarcane using the direct hydraulic press method*. *29*, 67–71.

Saranin, A. (1986a). The core-press system of sugar cane quality determination. *Proceedings 8th Annual Conference Australian Society of Sugar Cane Technologists*, 43–47.

Saranin, A. (1986b). The press method of sugarcane analysis. *Proceedings of the Australian Society of Sugarcane Technologists*, *8*, 33–42.

SASTA. (2009). *Laboratory Manual for South African Sugar Factories*. SASTA.

Sturion, A. C. (1977). *A study of core sampling and direct analysis of sugar cane*. 2937–2950.

Sturion, A. C., & Fernandes, A. C. (1975). Pagamento da cana-de-acucar pelo teor de sacarose. *Anais Do III Seminário COPERSUCAR Da Agroindústria Açucareira*, 79–100.

Tanimoto, T. (1964). The press method of cane analysis. *Hawaiian Planter's Record*, *57*(2), 133–150.

Turner, A. W., & Rojas, B. A. (1962). *Deterioration of sugar cane after cutting*. *11*, 312–318.

Wagenbreth, H., & Blank, W. (1971). *Official Journal of the Physikal Ische-Technische Bundesanstahlt, June*, 415–415.

Wright, P. G. (2005). Process Benchmarking in Cane Sugar Factories. *Proceedings Australian Society Sugar Cane Technologists*, *27*, 437–453.

Wright, P. G., Fernandes, A. C., & Zarpelon, F. (2007). Control calculations for factories producing both sugar and alcohol. *Proceedings of the 2007 Conference of the Australian Society of Sugar Cane Technologists Held at Cairns, Queensland, Australia, 8-11 May 2007*, *29*, 440–452.

Bibliography

- **SASTA - Southern Africa benchmark (2001-2017)**

Sugar Milling Research Institute, University of KwaZulu-Natal, Durban, 4041, South Africa

Davis S.B. (2002) - Seventy-Seventh Annual review of the milling season in Southern Africa (**2001**-2002) Proc SASTA (2002) 76.

Davis S.B. (2003) - Seventy-Eighth Annual review of the milling season in Southern Africa (**2002**-2003) Proc SASTA (2003) 77.

Davis S.B. (2004) - Seventy-Ninth Annual review of the milling season in Southern Africa (**2003** -2004) Proc SASTA (2004) 78.

Davis S.B. and Achary M. (2005) - Eightieth Annual review of the milling season in Southern Africa (**2004**-2005) Proc SASTA (2005) 79.

Davis S.B. and Achary M. (2006) - Eighty-first Annual review of the milling season in Southern Africa (**2005**-2006) Proc SASTA (2006) 80.

Davis S.B. and Achary M. (2008) - Eighty-second Annual review of the milling season in Southern Africa (**2006**-2007) Proc SASTA (2008) 81: 1 - 24.

Davis S.B. and Achary M. (2008) - Eighty-third Annual review of the milling season in Southern Africa (**2007**-2008) Proc SASTA (2008) 81: 25 - 50.

Davis S.B., Smith G.T. and Achary M. (2009) - Eighty-fourth Annual review of the milling season in Southern Africa (**2008**-2009) Proc SASTA (2009) 82: 1 - 29.

Smith G.T., Davis S.B., and Achary M. (2010) - Eighty-fifth Annual review of the milling season in Southern Africa (**2009**-2010) Proc SASTA (2010) 83: 1 - 28.

Smith G.T., Davis S.B. and Achary M. (2011) - Eighty-sixth Annual review of the milling season in Southern Africa (**2010**-2011) Proc SASTA (2011) 84: 37 - 65.

Smith G.T., Davis S.B., Madho S. and Achary M. (2012) - Eighty-seventh Annual review of the milling season in Southern Africa (**2011**-2012) Proc SASTA (2012) 85: 1 - 29.

Smith G.T., Davis S.B., Madho S. and Achary M. (2013) - Eighty-eighth Annual review of the milling season in Southern Africa (**2012**-2013) Proc SASTA (2013) 86: 24 - 54.

Smith G.T., Davis S.B., Madho S. and Achary M. (2014) - Eighty-ninth Annual review of the milling season in Southern Africa (**2013**/14) Proc SASTA (2014) 87: 23 - 52.

Smith G.T., Davis S.B., Madho S. and Achary M. (2015) - Ninetieth Annual review of the milling season in Southern Africa (**2014**/15) Proc SASTA (2015) 88: 23 - 54.

Smith G.T., Davis S.B., Madho S. and Achary M. (2016) - Ninety-first Annual review of the milling season in Southern Africa (**2015**/16) Proc SASTA (2016) 89: 21-51.

Madho S., Davis S.B., and Bhyrodeyal L. (2017) - Ninety-second Annual review of the milling season in Southern Africa (**2016**/17) Proc SASTA (2017) 90: 20-50.

Madho S., Essop, R., Visram K., Davis S.B., and Bhyrodeyal L. (2018) - Ninety-third Annual review of the milling season in Southern Africa (**2017**/18) Proc SASTA (2018) 91: 19-51.

- **Brazilian Portuguese publications**

Fernandes, A.C. (1984a) – "Representação matemática das tabelas de Lane & Eynon para análise de açúcares redutores". Boletim Técnico Copersucar, 26:30-35

Fernandes, A.C. (1984b) – "Determinação dos coeficientes da prensa hidráulica na análise direta da cana-de-açúcar". Boletim Técnico Copersucar, 27:13-20.

Fernandes, A.C. (2011) – "Cálculos na agroindústria da cana-de-açúcar"; 3ª Edição, Soc. Técnicos Açucareiros e Alcooleiros do Brasil (STAB) 416 páginas (www.stab.org.br).

Payne, J.H. (1990) – "Operações Unitárias na Produção de Açúcar de Cana". Ed. Nobel/STAB.

Sturion, A.C. & Fernandes; A.C. (1975). "Pagamento da cana-de-açúcar pelo teor de sacarose" Anais III Sem. COPERSUCAR Agroind. Açuc. p. 75-100.

Sturion, A.C. & Fernandes, A.C (1979) – "Análise direta da cana-de-açúcar pelo método da prensa hidráulica". Boletim Técnico Copersucar, 8:12-15, 1979.

Stuchi, A. & Zarpelon, F. (1995) – "Cálculo do rendimento industrial STAB"; STAB, 13(4):26-30.

Acronyms

ASSCT: Australian Society of Sugar Cane Technologists.

ASST: American Society of Sugarcane Technologists, United States of America.

ISSCT: International Society of Sugar Cane Technologists.

QSSCT: Queensland Society of Sugar Cane Technologists.

SASTA: South African Sugar Technologists' Association.

STAB: Brazilian Society of Sugar and Ethanol Technologists (Portuguese: "Sociedade dos Técnicos Açucareiros do Brasil").

ESALQ-USP: "Luiz de Queiroz" College of Agriculture – University of São Paulo (Portuguese: Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo).

Consecana-SP: Council of Cane, Sugar, and Ethanol Producers of the State of São Paulo (Portuguese: "Conselho dos Produtores de Cana, Açúcar e Etanol do Estado de São Paulo").

Int. Sug. J.: The International Sugar Journal

CTICS: Centre Technique Interprofessionnel de la Canne et du Sucre (Reunion)